BMP Planning to Address Urban Runoff

Chagrin Watershed Pilot

July 30, 2012

Prepared for

U.S. Environmental Protection Agency -- Region 5
Chagrin River Watershed Partners
Ohio Environmental Protection Agency

Prepared by

Tetra Tech, Inc.
1468 West Ninth Street, Suite 620
Cleveland, OH 44113

Contents

Figures

Tables

Acronyms and Abbreviations

BMP	best management practice
CRWP	Chagrin River Watershed Partners
CSM	Critical Storm Method
CSO	combined sewer overflow
CWA	Clean Water Act
GI	green infrastructure
GIS	geographic information system
GLM	Great Lakes Mall
GLRI	Great Lakes Restoration Initiative
HRU	hydrologic response unit
HSG	hydrologic soil group
HSPF	Hydrologic Simulation Program FORTRAN
HUC	hydrologic unit code
LA	load allocations
LEPF	Lake Erie Protection Fund
LID	low impact development
LSPC	Loading Simulation Program C++
MS4	municipal separate storm sewer system
NCDC	National Climatic Data Center
NPDES	National Pollutant Discharge Elimination System
NPS	nonpoint source
NWS	National Weather Service
Ohio EPA	Ohio Environmental Protection Agency
PCA	priority conservation area
PDA	priority development area
RM	river mile
RRI	retrofit reconnaissance investigation
SWMM	Storm Water Management Model
SUSTAIN	System for Urban Stormwater Treatment and Analysis INtegration
TMDL	total maximum daily load
UMN	University of Minnesota
USEPA	U.S. Environmental Protection Agency
WQv	water quality volume
WWH	warmwater habitat

Executive Summary

As part of the Great Lakes Restoration Initiative (GLRI), work is underway to strategically pilot implementation of the System for Urban Stormwater Treatment and Analysis INtegration (*SUSTAIN*) in several Great Lakes area watersheds. Problems resulting from stormwater runoff associated with urban development throughout the basin touch on each of the five focus areas of the GLRI. Many metropolitan areas in the Great Lakes region have waterbodies that are impaired due to stormwater sources, while thirty toxic hotspot Areas of Concern are still in need of cleanup. Because *SUSTAIN* identifies cost-effective methods to address problems caused by urban stormwater, the use of this tool is an essential part of the restoration plan.

This *SUSTAIN* project examined the applicability of the tool in three Great Lakes pilot watersheds: the Chagrin River in Ohio; the Salt Creek watershed in northwest Indiana; and the Amity Creek watershed near Duluth, Minnesota. The project is designed to identify recommendations for Best Management Practices (BMPs) on new development and to apply *SUSTAIN* as a tool to prioritize retrofit opportunities. This includes the use of green infrastructure (GI) in Combined Sewer Overflow (CSO) areas. In addition, these pilots serve as an opportunity to explore the use of *SUSTAIN* for determining stormwater utility credits. Results are expected to augment current efforts in promoting low impact development (LID) in these watersheds, support Watershed Action Plan / TMDL implementation, and inform development of MS4 permits. Based on the pilot applications, these case studies provide a template for future *SUSTAIN* applications in the region.

This technical report describes work conducted for the Chagrin River watershed pilot. Building on information in the Chagrin River Watershed Action Plan, a priority area (Ward-Newell Creek) was selected for testing of *SUSTAIN*. The approach used in this pilot effort employed a multi-scale analysis coupled with use of a five-step process to guide the application of the tool. Characterization data from development of the Chagrin River Watershed Action Plan and information on BMPs that have been implemented in the area were examined with *SUSTAIN*. Study results are presented in this document.

1. Introduction

The Chagrin River drains 267 square miles in four northeast Ohio counties (Figure 1-1). The river valley offers a diversity of aquatic communities, wildlife, unique rock outcroppings, and extensive headwater wetlands (CRWP 2009). Seventy-one miles of the Chagrin River have been designated as a State Scenic River. The watershed is experiencing significant development pressure as the Cleveland population continues to migrate from the urban core and inner ring communities to outlying suburbs. In spite of continued farming, residential, commercial and industrial development, the Chagrin River maintains high water quality and natural beauty.

The Chagrin River Watershed Partners, Inc. (CRWP) was formed by 16 cities, villages, townships, counties, and park districts in 1996 in response to increasing concerns about flooding, erosion, and water quality problems. Local concerns prompted development of the Chagrin River Watershed Action Plan in 2000 to help member communities address problems regarding natural resource management. In 2007, Ohio EPA prepared Chagrin River TMDLs for phosphorus, nitrates, habitat, bacteria, and total suspended solids. The primary causes of impairment in the watershed are organic enrichment, nutrients, flow alteration, and habitat degradation. Major sources of impairment include land development / suburbanization, sewage treatment plants, wetland filling, removal of riparian vegetation, urban stormwater and nonpoint sources.

In 2009, CRWP revised the Watershed Action Plan to include TMDL implementation, updating goals, and incorporating the Chagrin River Watershed Balanced Growth Plan. Under the revised Plan, CRWP and local stakeholders are focusing watershed management efforts on protecting existing open space, streams and wetlands; restoring those resources that have already been impacted; and influencing local development standards and practices to allow continued development while maintaining the high quality of the Chagrin River.

In 2010, CRWP began working with the U.S. Environmental Protection Agency (USEPA) Region 5 to test the System for Urban Stormwater Treatment and Analysis INtegration (*SUSTAIN*). The purpose and goals of this *SUSTAIN* pilot application include:

- Provide a summary of cost-effective Best Management Practices (BMPs) that will address existing stormwater runoff problems in the Chagrin River watershed.
- Provide a summary of optimal reduction strategies for runoff volumes and peak flows in a portion of one of the Chagrin River priority subwatersheds (Ward-Newell Creek).

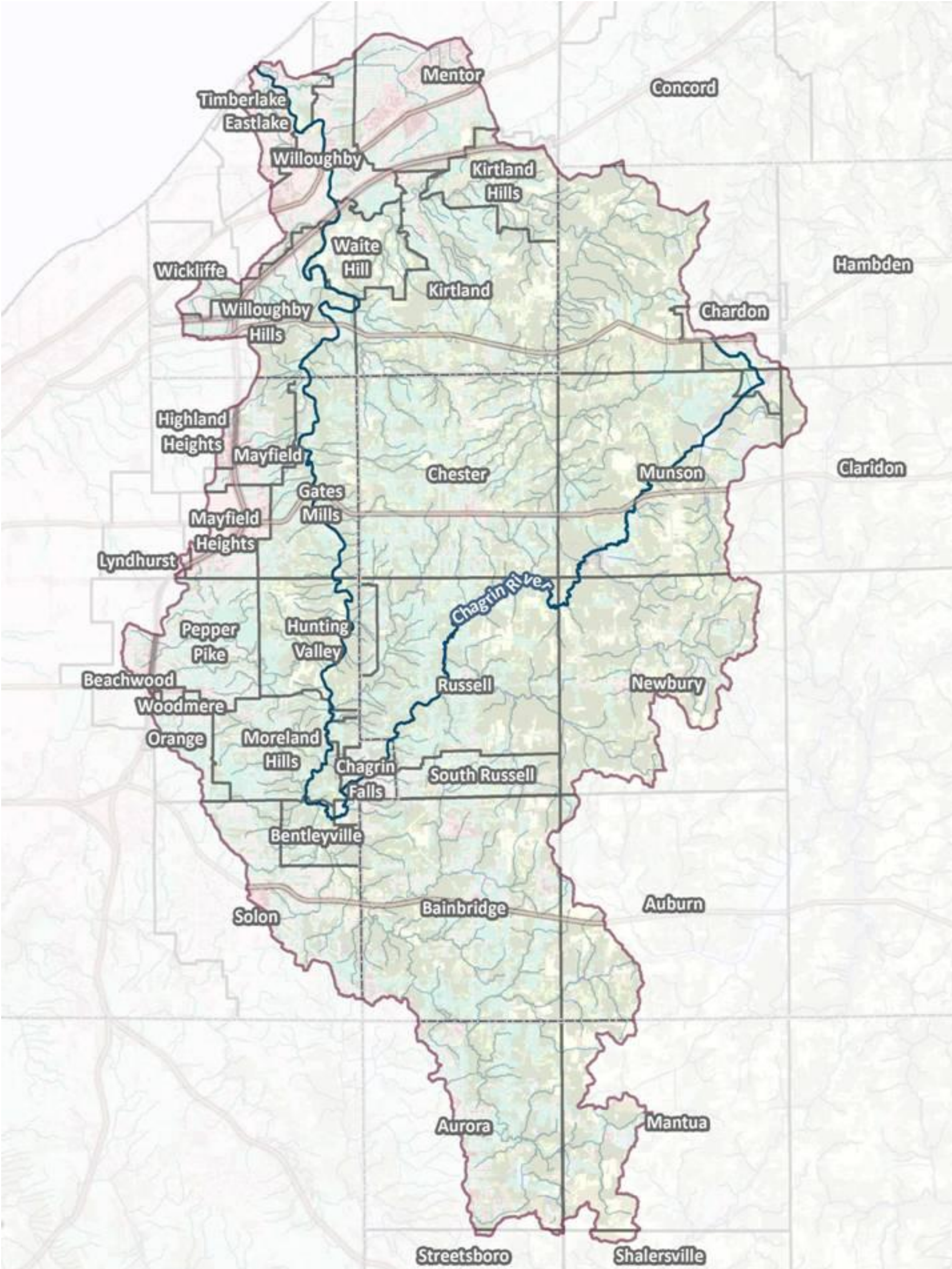


Figure 1-1. Chagrin River watershed.

2. Approach

Development of effective stormwater management strategies is an important part of the transition from water quality program planning to implementation. The underlying goal of this project is to provide technical support for local stormwater planning and implementation efforts. A major focus of the work is analyzing and selecting the most appropriate suite of BMPs to achieve targeted flow volume and / or pollutant load reductions.

The general approach used to develop this pilot effort considers two aspects related to watershed planning and implementation. The first involves using a framework to address the scale issues associated with watershed management. Project partners used a multi-scale analysis to examine problems caused by excess stormwater volumes and peak flows at the watershed level, building on information in the Chagrin River Watershed Action Plan. The multi-scale analysis moves to progressively smaller levels based on priority concerns and implementation opportunities.

The second aspect of the general approach is the use of a five-step process to identify optimal BMPs for the Chagrin River watershed. The five-step process was conducted in tandem with the multi-scale analysis, and involves (1) establishing baseline conditions; (2) identifying potential BMPs; (3) evaluating opportunities and constraints; (4) estimating costs; and (5) building a stormwater management strategy.

2.1 Multi-scale Analysis

Scale of analysis is an extremely important aspect of stormwater management. Any size land area can be selected for assessment. At the broadest scales (e.g., citywide), analyses of stormwater problems provide the context for policy formulation, laws, regulations, codes, and ordinances. At the finest scales (e.g., specific streets or residential lots), technical analyses provide the basis for project implementation and can be used to evaluate site-specific impacts. Mid-scale analyses (e.g., conducted at a watershed level) provide the context for management through the description and understanding of typical stormwater problems and the capabilities that exist to address those problems.

Stormwater management often occurs in the mid-scale range, which allows for broad pattern recognition and process identification that in turn sets priorities for subsequent analysis. Information at this scale is typically used to guide decisions facing MS4 jurisdictions. For example, an examination of water quality issues within a small urban watershed (e.g., 1,000 acres) might illustrate that a priority problem is stream channel instability caused by unnaturally high peak flows associated with new development. Controlling peak flow can therefore be established as a high priority for the stormwater program.

Mid-scale analysis, however, does not work well for certain aspects of stormwater planning and implementation. For example, a watershed manager might not know if it is more effective to reduce peak flows through retrofitting existing detention ponds, or promoting distributed BMPs such as residential rain gardens. Furthermore, differences in the design of different BMPs can have a big impact on their performance. Analyses at a site level are better able to assess the potential effects of specific management activities, because specific BMPs and design criteria for those BMPs can be evaluated.

Regardless of the physical area selected, each level of stormwater analysis should draw context from another and work together. For example, the technical assessment used to develop the Chagrin River Watershed Action Plan guides site-level project planning and decision-making by providing the overall watershed context.

Key problems and watershed goals are identified in the Watershed Action Plan; details of implementation should be determined through analyses at finer scales. In turn, lessons learned from site level planning (e.g., identification of the most cost-effective BMPs, including their design specifications) should be fed back to the Watershed Action Plan to provide refined context as management of the watershed progresses.

Stormwater managers should keep in mind that sometimes simplifying or generalizing the effects of management practices is appropriate. Sometimes very detailed simulation or testing of BMPs can be performed and the results extrapolated to a larger scale, with such studies described as *nested* modeling studies. A detailed evaluation of rain gardens or porous pavement, for instance, can be performed at the street scale using modeling or monitoring. Study results can then be used to evaluate the implications of using similar practices throughout the watershed.

In larger watersheds there are additional considerations in applying results to the entire watershed, as well as accounting for physical and chemical processes that occur on a large scale (e.g., in-stream nutrient uptake, the timing and duration of storm event peak flow at the mouth of the watershed). If the upstream conditions of a watershed significantly influence the downstream portions, it might be necessary to use a watershed model to evaluate the link between upstream and downstream indicators.

With these basic principles in mind, this pilot effort uses the following levels to address scale issues.

Level 1 examines water quality, flow, and general land use patterns at the watershed (10-digit HUC) and subwatershed (12-digit HUC) levels. Key information that affects stormwater (e.g., rainfall-runoff relationships; distribution of pollutant loads; identification of higher density development) is used to target priority areas for subsequent analyses (e.g. catchments several hundred acres in size; groups of catchments with similar land use patterns). Delineating catchments and estimating impervious cover associated with developed land use classes are important components of Level 1.

Level 1 utilizes the BMP assessment module of *SUSTAIN* to generate performance curves. These curves bracket a range of assumptions for more significant parameters (e.g., capture depth, infiltration rate) to evaluate potential BMP effectiveness. The emphasis in Level 1 is on practices that could be applied in priority catchments, which will lead to achieving reduction targets for stormwater volume, peak flow, and / or pollutant loads. Level 1 can also be used to evaluate key factors affecting BMP performance.

The example shown in Figure 2-1 illustrates the use of performance curves to examine the effect of different background infiltration rate assumptions on BMP performance. This figure demonstrates that the assumption for background infiltration rate has a relatively large effect on the predicted volume reduction and is therefore an important *SUSTAIN* input variable. Performance curves generated under Level 1 can be used to target areas within priority catchments where the use of certain BMPs might be encouraged (e.g., financial incentives offered through stormwater utility credits). In summary, the focus of Level 1 is to target priority areas for subsequent analyses and to highlight the sensitivity of key factors to be considered in identifying implementation opportunities or constraints that could prohibit the use of certain BMPs.

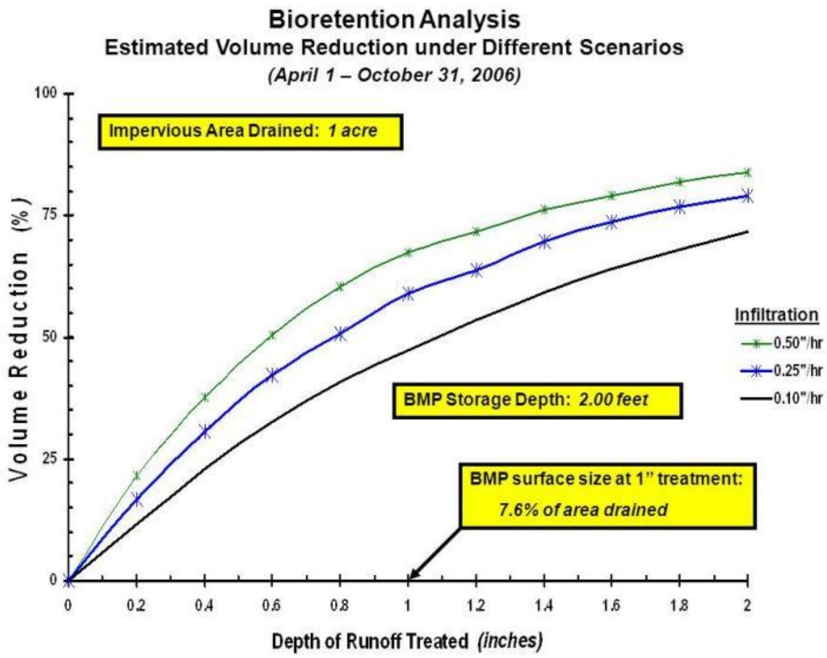


Figure 2-1. General BMP performance curve -- bioretention.

<u>*Level 2*</u> moves to a smaller scale by further examining the mix of development and impervious cover present in priority catchments. This information enables the Level 2 analysis to develop estimates volumes produced by various source areas (e.g., commercial parking, roads, residential roof). Figure 2-2 shows an example Level 2 schematic that serves as an organizational tool for determining where certain categories of BMPs could actually be implemented (e.g., pervious pavement for parking, streets, and driveways; rain barrels coupled with rain gardens for residential roofs).

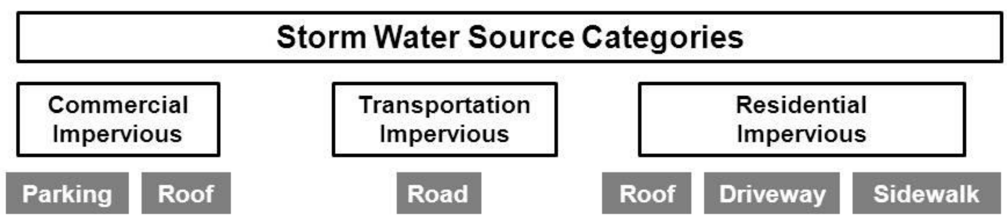


Figure 2-2. Stormwater source area types associated with Level 2 impervious cover analysis.

Because Level 2 is aimed at the catchment scale, the information on impervious cover type is more detailed. Example inventory data at this level includes: size of parking lots, street lengths and widths, number of homes, average driveway size, average roof size, sidewalk presence and size, etc. Prioritizing the impervious areas for treatment is also a component of Level 2. Pervious space is also inventoried; both for its contribution to runoff and for consideration of potential BMPs that could be incorporated into implementation planning.

Level 2 catchment inventories enable development of estimates that describe the maximum extent to which BMPs could be applied to each impervious surface type. In addition to assessing individual practices, Level 2 factors in the potential use of treatment trains (e.g., rain barrels followed by rain gardens, flow from porous pavement systems to bioswales, etc.). The Level 2 analysis utilizes the BMP assessment module of *SUSTAIN* to develop curves that describe reductions associated with different management strategies (basically, level of implementation curves). The application and utility of Level 2 is described in greater detail Sections 4 and 5.

Level 3 draws information from Levels 1 and 2 to expand the analysis to include costs. A Level 3 evaluation uses the cost and optimization features of *SUSTAIN* to develop trade-off curves, such as the one shown in Figure 2-3. Each of the hundreds of circles within this curve represents a separate modeling run scenario with different assumptions for the number, type, and characteristics of BMPs. This type of analysis is best applied at the neighborhood (200 to 500 acre) scale because it allows for a detailed assessment of the potential BMPs and their design specifications. The model simulates the ability of each of the practices individually, and in combination, to reduce peak stream flows, taking into account the site-specific characteristics of the project area. Calculations are made at an hourly scale over a multi-year period to provide a full assessment of the response to each individual storm. At the same time, *SUSTAIN* assigns a locally-derived cost to each practice to achieve a total cost for each scenario. Plotting the combination of effectiveness and total cost for each of the hundreds of model runs results in the graph shown in Figure 2-3. The set of solutions at the far left and far top creates a cost-effectiveness curve.

Figure 2-3. Example *SUSTAIN* trade-off curve.

2.1.1 Chagrin River Watershed

The Chagrin River watershed drains 267 square miles in four Northeast Ohio counties. Portions of twenty two municipalities, ten townships, and four park districts govern land use and other activities in the watershed. The Main Branch of the Chagrin River begins above Bass Lake in the City of Chardon and flows 48 miles before entering Lake Erie in the City of Eastlake. Along its path, the Main Branch is joined by the Aurora Branch and the East Branch. The watershed is experiencing significant development pressure as the Cleveland population continues to migrate from the urban core and inner ring communities to outlying suburbs. However, the majority of the river retains its riparian forest cover and nearly fifty percent (50 percent) of the land in the watershed is zoned for low density, large lot residential uses.

Glacial activity shaped the watershed with resulting soils and geologic deposits contributing to the high quality and varied habitats of the watershed. There are many areas on the Chagrin River and its numerous tributaries where thick glacial till has eroded, exposing sandstone and Chagrin Shale bedrock. Soils with clayey textures in the subsoil that formed in glacial till predominate in the watershed. The geology of the Chagrin River watershed creates numerous issues for watershed management and land development including: erosion, stormwater runoff, and septic suitability. Rapid runoff and erosion are significant concerns through much of the watershed because of the proximity of bedrock to the surface, the instability of the glacial deposits, and the steepness of the valley areas (CRWP 2009).

Historically one of the problems in the Chagrin River watershed has been the concern of flooding and associated damage. Flooding on a large scale due to high river flows and localized flooding continue to be a major concern in the watershed. Data suggest that annual peak discharges have increased significantly over the past century, which have resulted in increases in the river's bankfull event frequencies and flood stage height. Increases in the bankfull event may cause changes in channel geometry and may accelerate stream bank erosion and downstream sedimentation (CRWP 2009).

Today the primary land use in the Chagrin River watershed is low density residential, with two acres per home representing about half of the developed area of the watershed. Based on an impervious cover study completed by CRWP in 2004, approximately 13 percent of the Chagrin River watershed communities are either zoned as open space or are protected by a park district or conservation easement. Under existing zoning, the watershed at build out would be comprised of 79 percent residential, of which 46 percent would be low density residential, 8 percent commercial/retail/industrial and 13 percent open space including properties currently protected by a park district or conservation easement (CRWP 2009).

The lower Main Branch of the Chagrin and tributaries are the most densely developed areas of the Chagrin River watershed due to their vicinity to the City of Cleveland. Streams in this part of the watershed include:

- Chagrin River Main Stem (mouth to river mile 4.6)
- Corporation Creek
- Ward/Newell Creek

Problems in this part of the watershed stem from alteration of habitat, riparian vegetation removal, channelization, development in the 100-year floodplain and the upstream effects of changing land use with associated increased urban stormwater runoff. These problems need to be addressed to improve water quality in this part of the watershed, as these are the same problems that threaten the rest of the Chagrin River watershed. For these reasons the *SUSTAIN* project focused on the Ward/Newell Creek subwatershed to identify the most appropriate BMPs to address urban stormwater runoff.

2.1.2 *Ward / Newell Creek*

Ward / Newell Creek is tributary to the Lower Chagrin River subwatershed (HUC 04110003-030-010), entering the main channel one mile upstream of Lake Erie. In the City of Mentor, the stream is referred to as Newell Creek, while it is called Ward Creek in the Cities of Eastlake and Willoughby. Approximately 28 percent of the watershed area is covered with impervious surfaces. Ohio EPA data shows that small urban streams with greater than 15 percent impervious cover have a lowered probability of meeting water quality standards to protect aquatic life uses, while those exceeding 25 percent imperviousness are not at all likely to attain standards. A majority of the impervious surfaces are in the upper reaches of the Ward / Newell Creek watershed. The lower corridor of this stream in Willoughby and Eastlake is in a green space corridor, partially protected by Lake Metroparks. However this section still does not meet Ohio EPA standards largely due to the stormwater discharges and habitat modifications. Further upstream in the City of Mentor, numerous segments of this stream have been piped.

Ward / Newell Creek is designated as a Warmwater Habitat (WWH) stream. This use represents the principal restoration target for the majority of water resource management efforts in Ohio. Based on 2003-2004 Ohio EPA sampling, Ward / Newell Creek in Eastlake at the Robin Road pump station is in non-attainment of the WWH aquatic life use due to sedimentation and erosion from flow alteration and nutrient inputs and organic enrichment from suburban / urban runoff and storm sewers. Ohio EPA also noted excessive stormwater effects, such as down-cutting, bank erosion, and sedimentation.

The Ward / Newell Creek subwatershed is approximately 7.8 square miles (4,980 acres) comprised of mostly urban land uses, including commercial, industrial, and higher density residential. Approximately 28 percent of this area is covered by an impervious surface such as roads, buildings, or parking lots as shown in Figure 2-4. Due to the age of the development in this area (which occurred during a period before current regulations), much of this impervious cover may not have comprehensive stormwater management. Approximately 5 percent (245 acres) of the subwatershed is open space as park land or vacant municipal property as shown in Figure 2-5. The City of Willoughby Lost Nation Golf course is highlighted as recreational. Because the golf course is City owned, restoration opportunities may still exist on this property. The City of Eastlake has acquired a series of properties that are managed by Lake Metroparks along the lower reaches of Ward / Newell Creek. Figure 2-5 shows the streams, associated Federal Emergency Management Agency designated floodplains and location and types of open space.

The Cities of Eastlake, Willoughby, and Mentor all participated in the Chagrin River Watershed Balanced Growth Plan. Development of this plan identified and endorsed priority conservation areas (PCAs) and priority development areas (PDAs), as shown in Figure 2-6. Within the Ward / Newell subwatershed, the PDAs include commercial and industrial zones property where development already exists or redevelopment may occur. The PDAs also identify future growth in the southeast portion of the subwatershed, specifically in the Newell Creek development off Norton Parkway. PCAs include riparian corridors, existing parks, Lost Nation Golf Course, conservation easements, planned open space in the Newell Creek Development, and large parcels that may be possible open space or conservation easements.

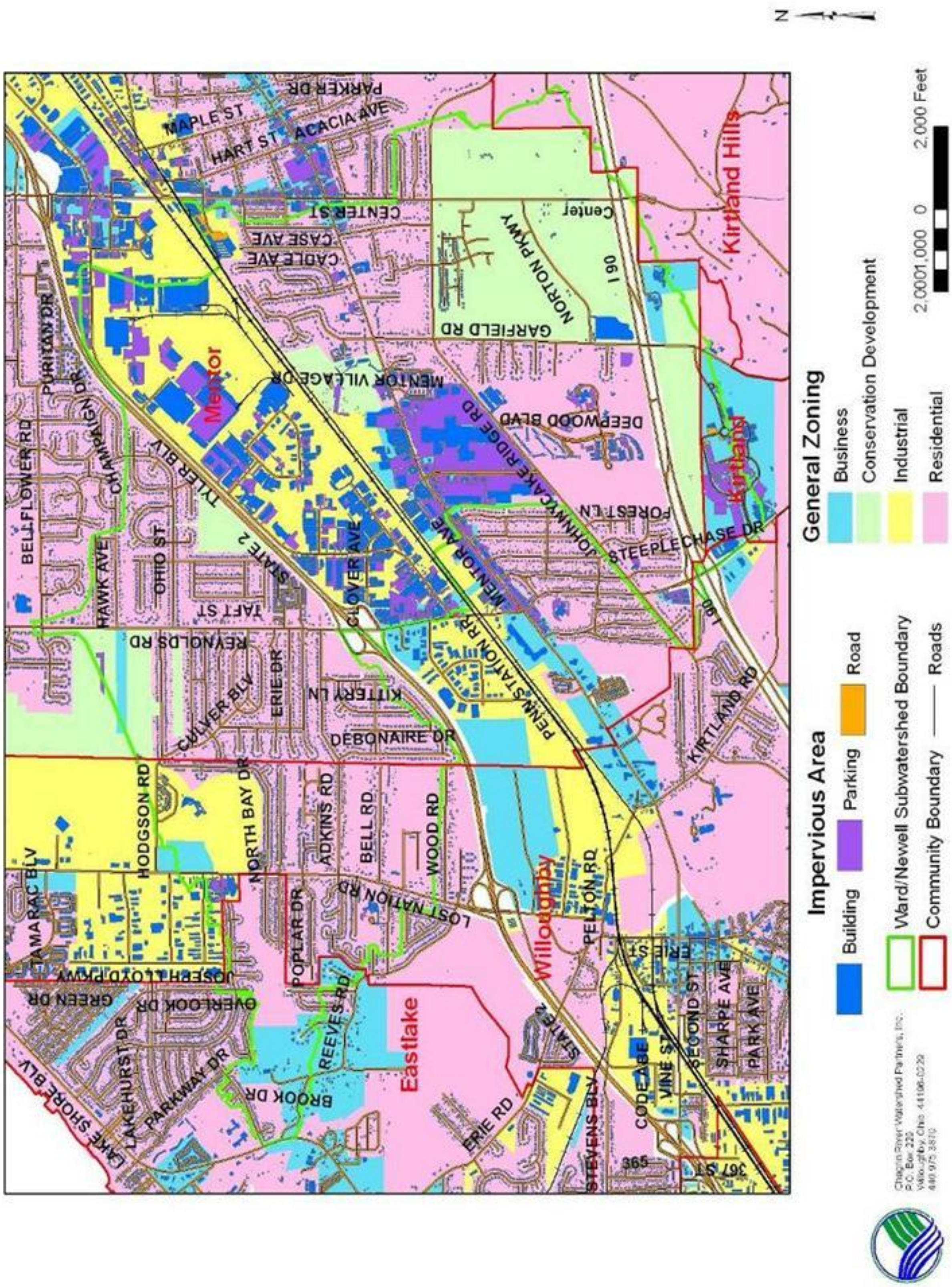


Figure 2-4. Ward / Newell impervious areas.

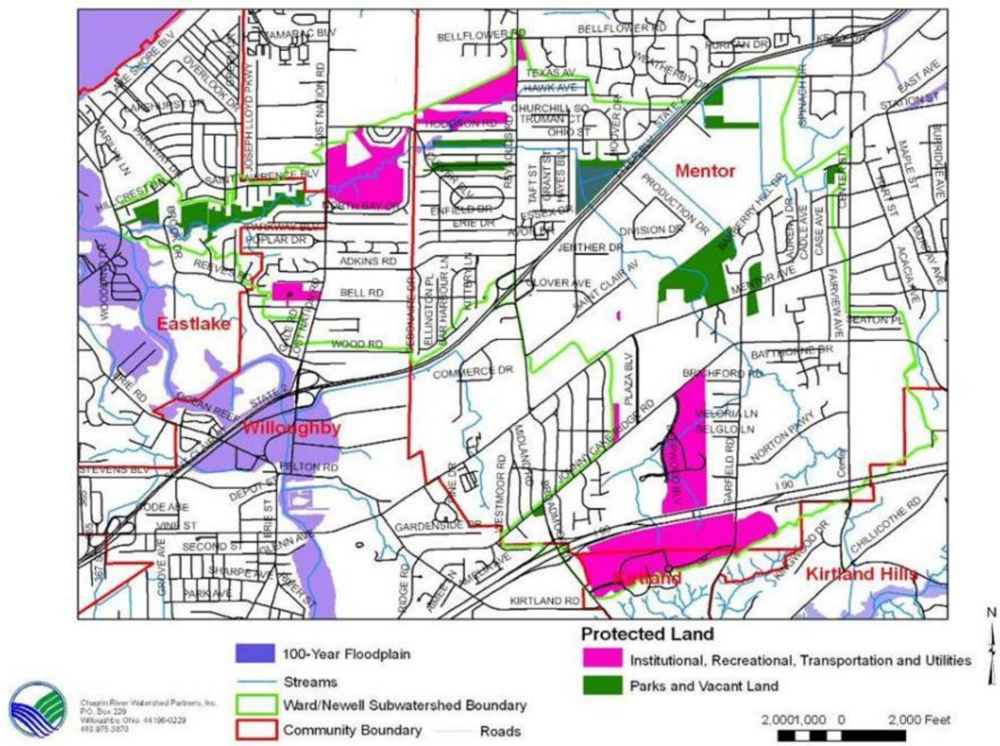


Figure 2-5. Ward / Newell floodplain and open space.

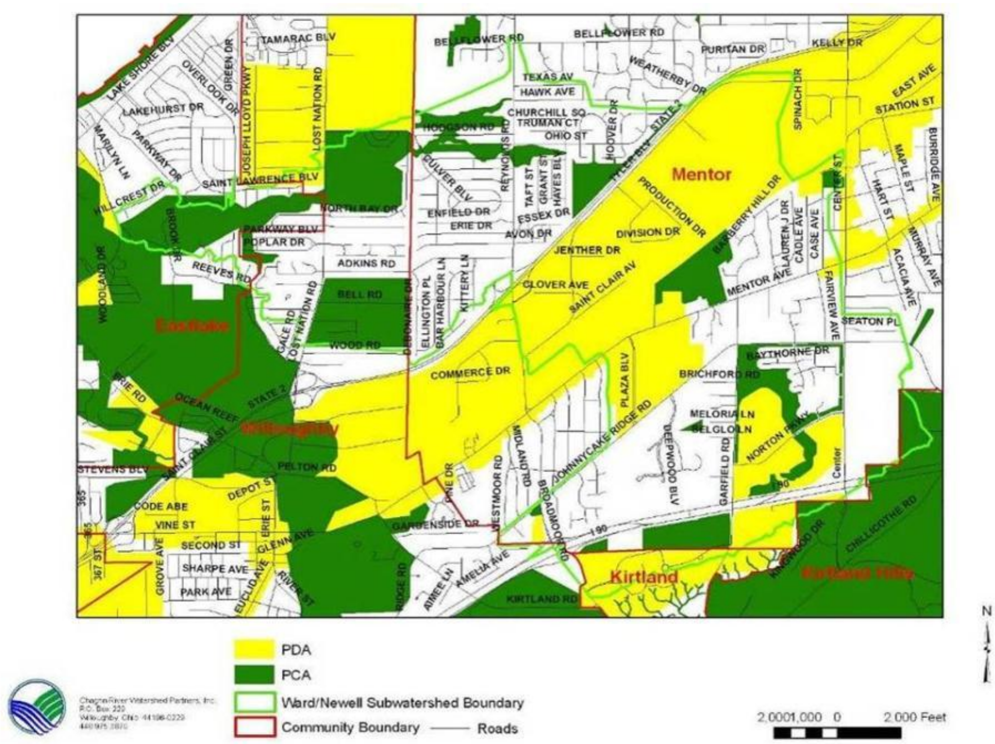


Figure 2-6. Ward / Newell priority conservation and priority development areas.

Water Quality

Ward / Newell Creek was sampled at a single location at RM 0.80 near the Robin Road pump station during the 2003 / 2004 Ohio EPA sampling. No significant wastewater treatment plants discharge to Ward / Newell Creek. However, urban runoff is extensive; it originates from residential and commercial sources as well as a golf course and airport. Biological survey results indicate that Ward / Newell Creek is in non-attainment of its WWH aquatic life designated use. However, no specific chemical stressors were identified.

Fish communities in Ward / Newell Creek were rated as *Fair* and are impaired by hydrologic alteration, sedimentation, and toxicity from urbanization. This is likely due to the fact that the Ward / Newell Creek subwatershed drains the highest amount of impervious surfaces in the Chagrin watershed. The Ward / Newell Creek macroinvertebrate community quality is affected by an upstream wastewater treatment plant and diffuse nonpoint source inputs. Relative organism density was high and attributed to nutrient enrichment and increased primary production. High relative densities of caddisflies, filtering midges, and facultative mayflies were predominant in the riffle/run habitats. While sampling, solids and algal mats were observed in the slower runs and margins. Much less diverse and more tolerant biota were collected laterally from the more oxygenated thalweg (center of the main flow channel). The stream color was murky grey to green. Fair macroinvertebrate community quality was documented with 25 total taxa and only four EPT and sensitive taxa collected. Better wastewater treatment, stormwater runoff controls, and improved riparian corridor thickness and canopy cover would improve the biological community quality. The Quality Habitat Evaluation Index score meets the WWH criteria for this stream.

Ohio EPA noted that: *A future survey will need to be conducted for the Ward Creek watershed to identify the causes and sources of the documented non-attainment for biological communities. Excessive water energy from impervious area runoff, siltation and loss of riparian habitat are likely stressors on biology given the urban nature of the watershed, and should be the focus of future water quality studies.*

Stormwater Management Objectives

Biological survey results indicate that Ward / Newell Creek does not attain its WWH aquatic life designated use. Stormwater sources in the drainage contribute to hydrologic alteration, sedimentation and toxicity that have an adverse effect on fish and macroinvertebrate communities. Although a TMDL was developed for the Chagrin River watershed, no targets were identified for Ward / Newell Creek. Ohio's stormwater management program, however, includes the use of water quality volume (WQv) that can be used to identify quantitative objectives for this project.

Controlling runoff volume is key to minimizing damage and costs associated with flooding and severe stream erosion, as well as to achieving water quality standards (Dorsey et al. 2009). WQv has two stream protection objectives: reducing pollutants suspended in runoff (water quality protection); and reducing the energy of common storm events responsible for most stream erosion (channel protection).

Stormwater Management Opportunities

Development Regulations. The creation and implementation of development regulations is vital to maintain existing natural resources and stormwater management. The Ward / Newell subwatershed is located in three Lake County communities; the majority in the City of Mentor with portions in the Cities of Willoughby and Eastlake, and all located in Lake County. Below is a list of development regulations each community has adopted that protect the natural resources:

- Erosion and Sediment Control
- Comprehensive Stormwater Management
- Illicit Discharge and Detection
- Flood Damage Reduction regulations

CRWP also recommends the adoption of these additional development regulations:

- Riparian and Wetland Setbacks
- Conservation Development
- Parking Regulations that decrease unused impervious surface

Discussions have taken place with each community to educate them on the protection of water quality, as well as flood reduction and economic savings the adoption and implementation these regulations can bring. CRWP continues to encourage these communities to further pursue the adoption of these regulations.

Focus Areas and Potential Projects. Using the *Center for Watershed Protection Retrofit Reconnaissance Investigation* (RRI) forms and a Geographic Information System (GIS) database, CRWP analyzed the Ward / Newell Creek subwatershed to locate potential stormwater retrofits and areas for stream protection and restoration opportunities. Much of the focus for stormwater retrofits is in the City of Mentor. This is because upstream flow management to reduce peak flow and runoff volume would be necessary prior to completing any downstream restoration in the more naturalized stream segments in Willoughby and Eastlake.

Initially eight sites with retrofit, protection, and/or restoration potential were compiled using the RRI forms. Aerial maps of each site were created including pertinent property information, and additional questions about the sites were presented to the City of Mentor. An effort was made to focus on potential restoration and retrofit locations that are on public property or easements. The obvious exception to this is the Great Lakes Mall. As the Great Lakes Mall has implications for flooding, water quality and economic development, it is the highest priority to CRWP and the City of Mentor.

Figure 2-7 details specific locations for potential stormwater retrofits, protection, and restoration projects within the Ward / Newell Creek corridor. The potential opportunities are detailed below including a discussion on specific projects.

Great Lakes Mall is located north of Johnnycake Ridge Road and south of Mentor Avenue. The mall constitutes a large contiguous area of impervious cover to Ward / Newell Creek. As a result, it is the highest priority for stormwater retrofit and green infrastructure (GI) for both CRWP and the City of Mentor. The City of Mentor has been involved in conversations with representatives of the Great Lakes Mall regarding potential renovations to the mall. Any potential LID practices implemented on the mall site would reduce impervious area and increase green space. LID practices could also create potential outdoor spaces around the mall for shoppers to enjoy and increase the economic viability of the mall.

Thus stormwater retrofits and redevelopment could work together to make a more economically viable shopping center.

Stormwater management for this site currently consists of a drainage network with no detention or infiltration facilities. CRWP is continuing to model specific BMPs such as a gravel wetland or a series of bioretention areas to provide much needed stormwater quantity and quality management. Use of BMP targeting and optimization models (e.g., BMP Decision Support System and *SUSTAIN*) could evaluate different scenarios to find the most cost-effective stormwater management option.

Upper Ward / Newell. From the southwest corner of the watershed a branch of Ward / Newell Creek flows through existing development with limited stormwater management into a 73 acre parcel of land that is noted for future development. This parcel has significant frontage on Johnnycake Ridge Road just west of Deepwood Boulevard and is zoned for residential development. It is critical that the stream corridor be protected during the site design of this development and that effective stormwater BMPs for both quantity and quality are installed as this area develops.

The stream flows east towards Deepwood Boulevard where approximately 880 linear feet of stream has been piped from Deepwood Boulevard to the east. The property is owned by Lake County and may provide opportunities for *daylighting the Deepwood Boulevard stream* in the future. The velocity of flow through this culvert appeared to create a channelized stream downstream of this area on the property owned by the City of Mentor south of Ridge Middle School. Although this stream has a wooded riparian corridor, the stream is channelized with no accessible floodplain, as seen in Figure 2-8 and Figure 2-9.

CRWP has recommended excavating an appropriate floodplain width at an elevation accessible to the stream to complete the Ridge Middle School Stream Restoration. Residents downstream on Stoneybrook Drive have frequent flooding concerns immediately downstream of this proposed restoration area. This stream restoration would create additional floodplain storage volume to detain and slow the flow of stormwater. To immediately address the concerns of the Stoneybrook residents, the City of Mentor is pursuing funding to replace the twin culverts under Stoneybrook drive with a larger culvert or box culvert to minimize the higher stream flows backing up at this point.

In the southeast corner of the watershed, the main channel of Ward / Newell Creek flows through the Newell Creek Development. This area is a mixed use development including office, residential, recreational, and open space that has not been built out to its planned capacity. A regional stormwater detention pond has been constructed to manage the stormwater from much of this development. As the development plans are finalized, the City of Mentor should ensure that this regional detention basin will provide adequate stormwater management. In addition, the Chagrin River stormwater permit may require additional infiltration practices for the water quality volume. The developed residential areas on the southern portion of the site drain to an upper detention basin in the development. This upper basin treats the stormwater and discharges to the lower basin which ultimately drains across the intersection of Johnnycake Ridge Road and Garfield Road into Ward / Newell Creek.

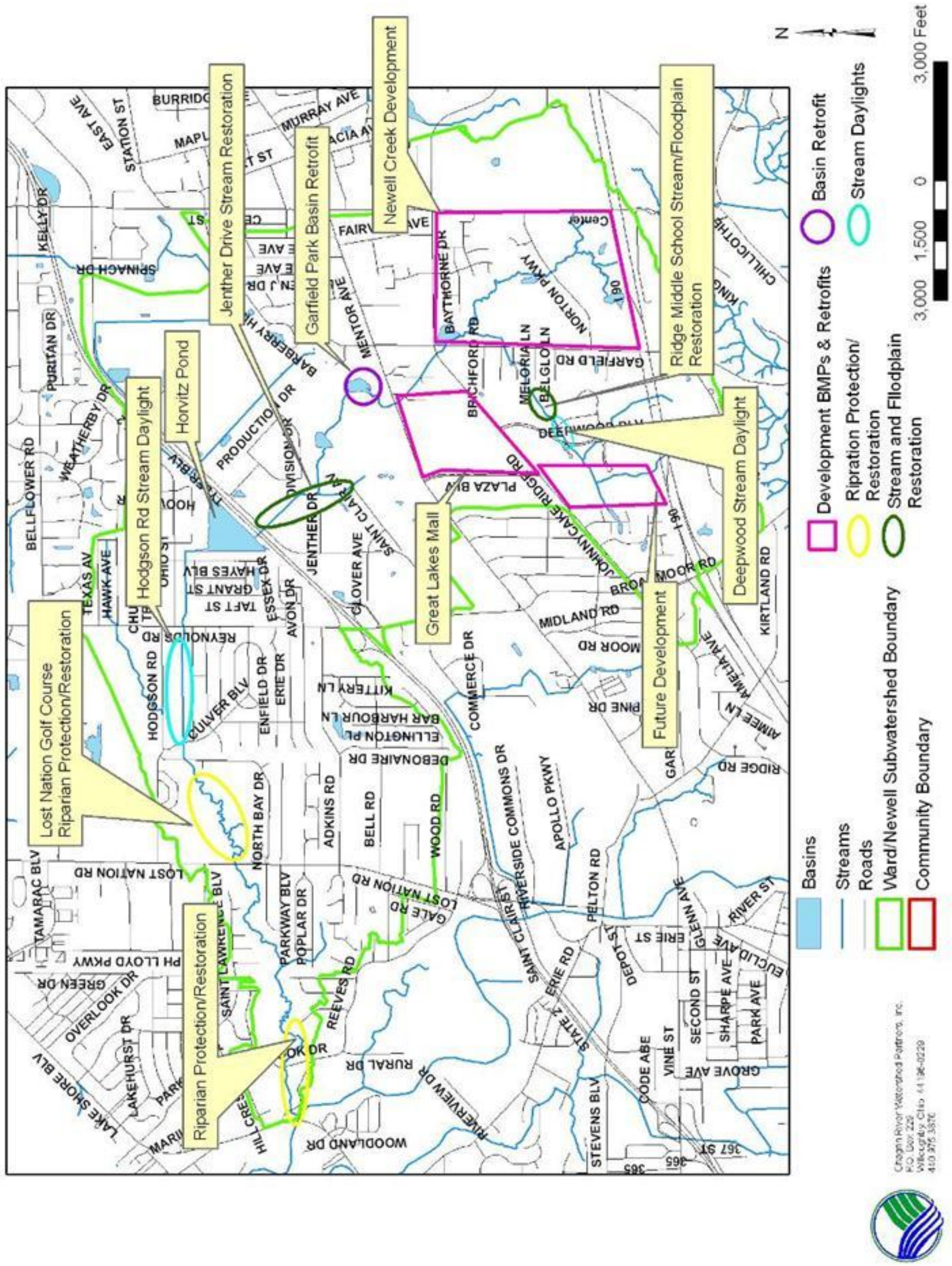


Figure 2-7. Potential retrofit, stream protection, and restoration opportunities.

Figure 2-8. Stream channelization in the upper Newell Creek watershed.

Figure 2-9. Air photo of channelized area in the upper Newell Creek watershed.

The tributary that drains the Deepwood Boulevard and Ridge Middle School area also drains onto the Newell Creek Development area at the northwest corner of the site. This tributary flows along the lower detention basin described above. At higher stream flows, water is allowed to overflow into this pond. The overflow is facilitated by placing a steel plate over a portion of the box culvert under Garfield Road so that when the stream reaches a certain level it backs up into the Newell Creek Development lower detention basin.

Garfield Park is located downstream of the Great Lakes Mall (Figure 2-10 and Figure 2-11). Situated between the mall and the park, a group of apartment buildings experience regular flooding in their parking areas. The parking is located directly next to the stream at a very similar elevation. CRWP and the City of Mentor have discussed several opportunities to create an additional floodplain storage area to slow the flow down before it reaches the Garfield Park Pond.

Garfield Park Pond has the highest potential for retrofit opportunities because it is within a City-owned park. Dredging accumulated sediment from this pond could reclaim some of its original storage volume. Further, modifying the outlet structure by both lowering the principal outlet structure and adding an additional outlet structure at a higher elevation would provide additional storage during storm events flow with a gradual outflow of this additional storage volume.

Figure 2-10. Garfield Park Pond.

Figure 2-11. Air photo of Garfield Park Pond area.

Other Opportunities. Another potential area for stream restoration is located east of *Jenther Drive*, off of Tyler Boulevard and west of Production Drive. Ward/Newell Creek is channelized through this industrial/commercial area. CRWP is currently discussing the possibility with the City of Mentor of creating additional floodplain storage along this corridor if the City of Mentor has a stormwater easement on this stream and the surrounding corridor. Ultimately all of the areas described above drain to Horvitz Pond. According to the City of Mentor, Horvitz Pond was retrofitted in 1988 to provide more flood volume while not allowing the system to surcharge and back up into neighboring subdivisions as was its historic nature. The retrofit provided storage up to the 25-year, 24-hour storm and releases the flow at a 5-year rate. Since this retrofit was completed, the system has been working efficiently to reduce localized flooding, however this retrofit was not designed to improve water quality.

The portion of stream that flows behind the homes on Hodgson Road is currently in a pipe with an overflow concrete channel above it (Figure 2-12). The Hodgson Road stream could be daylighted to restore a natural stream channel with riparian vegetation. After having discussions with Mentor, it appears that the residents along this portion of stream and downstream of it have not had complaints so this will not be one of the highest priority restoration sites. In addition, CRWP does not recommend completing this work until additional stormwater storage has been created upstream.

Figure 2-12. Ward / Newell Creek near Hodgson Road.

The lowest reaches of Ward/Newell Creek flow through the Lost Nation Golf Course owned by the City of Willoughby (Figure 2-13). There are numerous areas where mowing is occurring up to the edge of the stream. Restoration opportunities include creating a continuous forested riparian corridor in this reach and providing protection measures such as setbacks or easements.

The City of Eastlake and Lake Metroparks have protected a significant length of Ward/Newell Creek from Lost Nation Boulevard to the mouth. CRWP recommends that additional easements or land purchase be acquired to extend this protected area to the mouth of Ward/Newell Creek. Figure 2-14 highlights the potential properties for additional protection.

Figure 2-13. Ward / Newell Creek at Lost Nation Golf Course.

Figure 2-14. Ward / Newell Creek from Lost Nation Golf Boulevard to mouth.

2.2 Study Areas

Within the Ward / Newell watershed, two study areas were selected for evaluating *SUSTAIN's* capability to support CRWP's stormwater management objectives: Great Lakes Mall and Mentor Estates (Figure 2-15). One of the objectives of this pilot effort is to use the tool to examine a range of land uses. The Great Lakes Mall is 104 acres of commercial property (nearly 80 percent parking and just over 20 percent roof). As discussed earlier, this location represents the largest contiguous area of impervious surface in the Ward / Newell watershed. In contrast, the Mentor Estates area is 218 acres of single family residential land use. This test site is located in the City of Mentor on the south side of Ward / Newell Creek (opposite Hodgson Road). There are currently no stormwater management facilities within this area.

2.2.1 Key Questions

In contemplating the use of *SUSTAIN* to assess BMP opportunities and constraints, key questions can guide planning efforts. These questions bracket the range of viable options and ultimately help frame stormwater management decisions. Relative to this pilot effort, key questions include:

- Where and what amount of Great Lakes Mall parking area could be converted to bioretention or pervious pavement to meet a volume reduction target?
- Do bioswales offer viable options? Are there any suitable locations where infiltration trenches could be used (e.g., at the Great Lakes Mall)?
- How many homes in Mentor Estates need to install rain gardens to achieve noticeable reductions in stormwater volume? Where would be the best locations to target? And what are some treatment train design alternatives (including use of rain barrels)?
- What is the minimum acceptable operation and maintenance needed?
- How do assumptions associated with the different scales affect information needed by stormwater program managers to make subsequent decisions regarding development of cost-effective strategies?

2.2.2 Great Lakes Mall

The Great Lakes Mall (GLM) is located in Mentor between Mentor Avenue, Johnnycake Ridge Road, and Plaza Boulevard (Figure 2-16). GLM has around 150 stores and was opened in 1961, making it the first major enclosed mall in Ohio. It is owned by Simon Property Group and contains about 1 million square feet. GLM recently completed a major renovation that includes re-designed mall entrances and landscaping. The overall GLM test area encompasses 104 acres of mall parking lot and rooftop. Drainage from the test area is directly to upper Newell Creek through an outfall in the northeast corner of the subwatershed under Mentor Avenue.

Recently, the City of Mentor was awarded a Lake Erie Protection Fund (LEPF) grant to lay the foundation for addressing stormwater runoff concerns related to the GLM parking lot. The grant, from the Ohio Lake Erie Commission, is intended to gather preliminary information that will guide the installation of a pervious pavement / sustainable landscape system on a portion of the parking lot. Initial work will conduct soil test borings and develop a conceptual site plan that includes a preliminary cost estimate. The project supports the Chagrin River Watershed Balanced Growth Plan and the Chagrin River Watershed Action Plan.

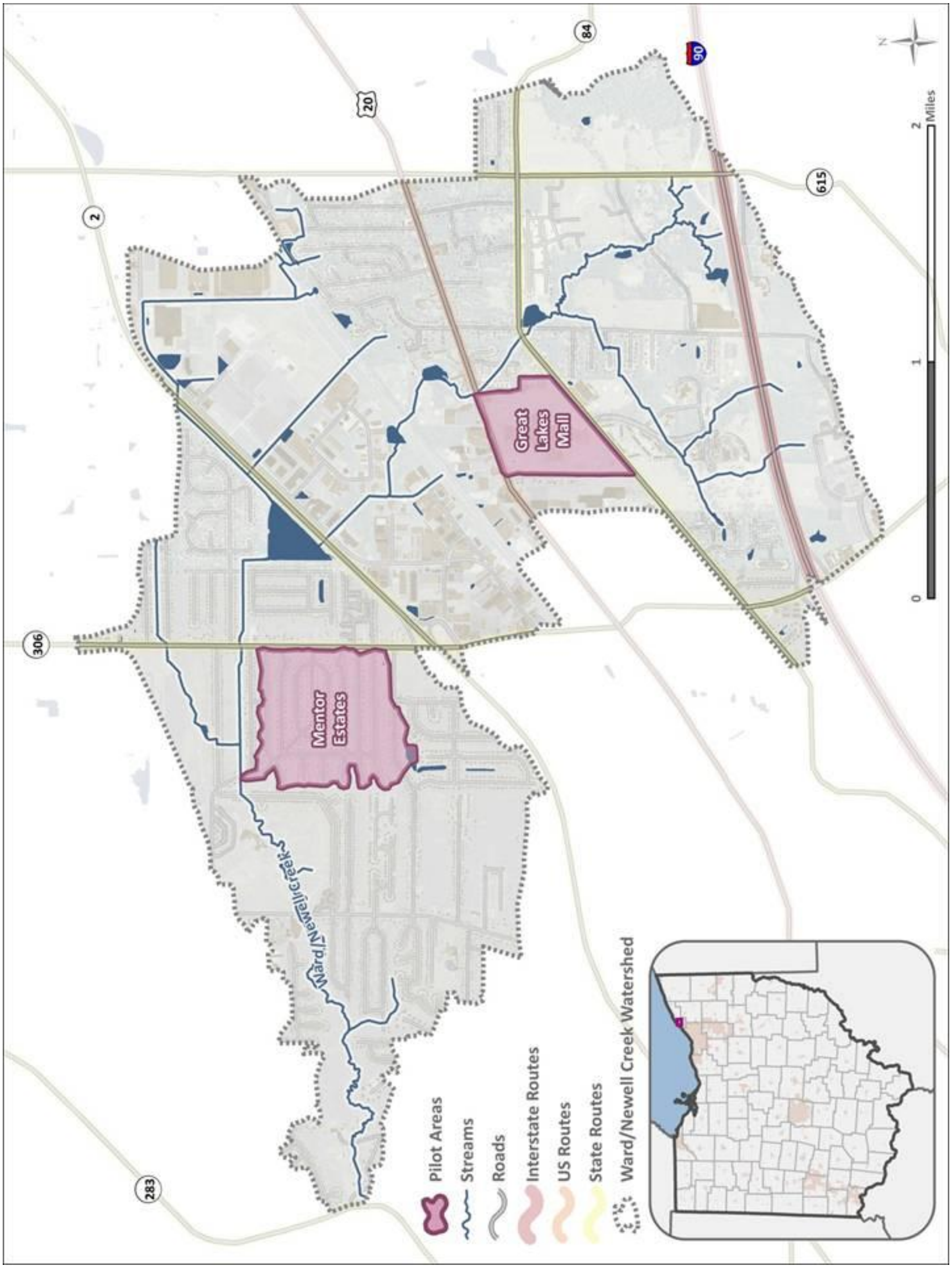


Figure 2-15. Ward / Newell watershed *SUSTAIN* test areas.

Figure 2-16. Air photo of GLM test area.

In order to represent the GLM within *SUSTAIN*, the GLM test area was delineated into six subwatersheds ranging in size from nearly six acres to just over 25 acres (Figure 2-17). Subwatersheds 1 through 5 are used for parking and vehicle traffic totaling approximately 80 acres, and are under consideration for reduction of effective impervious surface through GI and LID practices. Subwatershed 6 is the roof area of the mall and is not considered in this study for BMP opportunities although it has been included in the model for future efforts. Table 2-1 summarizes the size of each sub-shed, if it flows to another sub-shed or to the outlet of the mall area, and potential BMPs under consideration.

Table 2-1. GLM subwatersheds.

<table>
<tr><th>Sub-shed</th><th>Size (acres)</th><th>Flows to</th><th>Potential Practices</th></tr>
<tr><td>1</td><td>25.38</td><td>Out</td><td>o Bioretention & infiltration (east side parking area)</td></tr>
<tr><td>2</td><td>13.36</td><td>3</td><td rowspan="3">o Bioretention
o Infiltration
o Underground detention with infiltration</td></tr>
<tr><td>3</td><td>17.53</td><td>Out</td></tr>
<tr><td>4</td><td>18.62</td><td>2</td></tr>
<tr><td>5</td><td>5.76</td><td>Out</td><td>o Possible pervious pavement</td></tr>
<tr><td>6</td><td>23.36</td><td>Out</td><td>o Roof drainage (no alternatives)</td></tr>
</table>

In addition to information used to develop hydrologic response units (HRUs), detail spatial datasets of stormwater infrastructure (pipes and manholes) for the GLM project area were provided by CRWP and the City of Mentor (Figure 2-18).

A map showing the hydrologic soil groups (HSG) for the GLM project area is presented in Figure 2-19. While the areas around the mall show good infiltration potential with Type A and B soils, the mall area itself is marked as urban. This designation is generally used for areas that are paved, compacted, in-filled with non-native soil material or otherwise altered. The results of local infiltration testing under the LEPF grant are pending for the GLM.

A map showing percent slope for the GLM test area is presented in Figure 2-20. Analysis of the distribution of slopes within the study area reveals that the values range only between zero and one percent suggesting that the site is extremely flat. Areas that show slopes greater than 1.5 percent appear to be influenced by buildings or other structures on the site. For these reasons slope was excluded from the final HRU development for the GLM test area.

A map showing the distribution of surface cover types for the GLM study area is presented as Figure 2-21. An overlay of soil and impervious surface type was performed using the two raster layers described above. Impervious surfaces were given priority in the overlay meaning that only areas not already marked as impervious were considered pervious. As discussed, the slope raster was excluded from development of HRUs for the GLM. This overlay resulted in a distribution of five unique HRU categories that capture the physical texture of the subwatersheds. Finally, Figure 2-22 presents a map showing the resulting HRU distribution within the GLM study area.

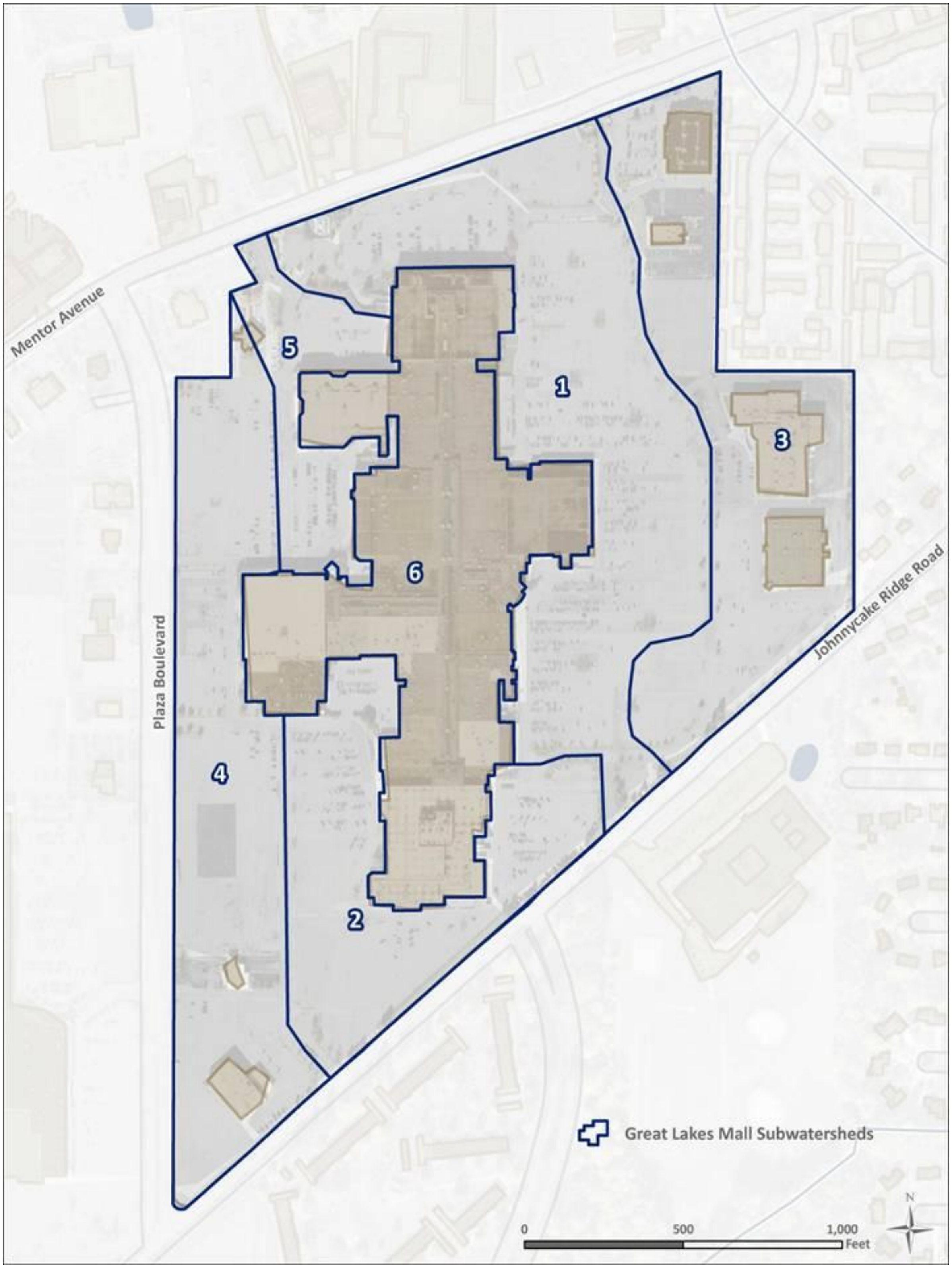


Figure 2-17. GLM test area subwatersheds.

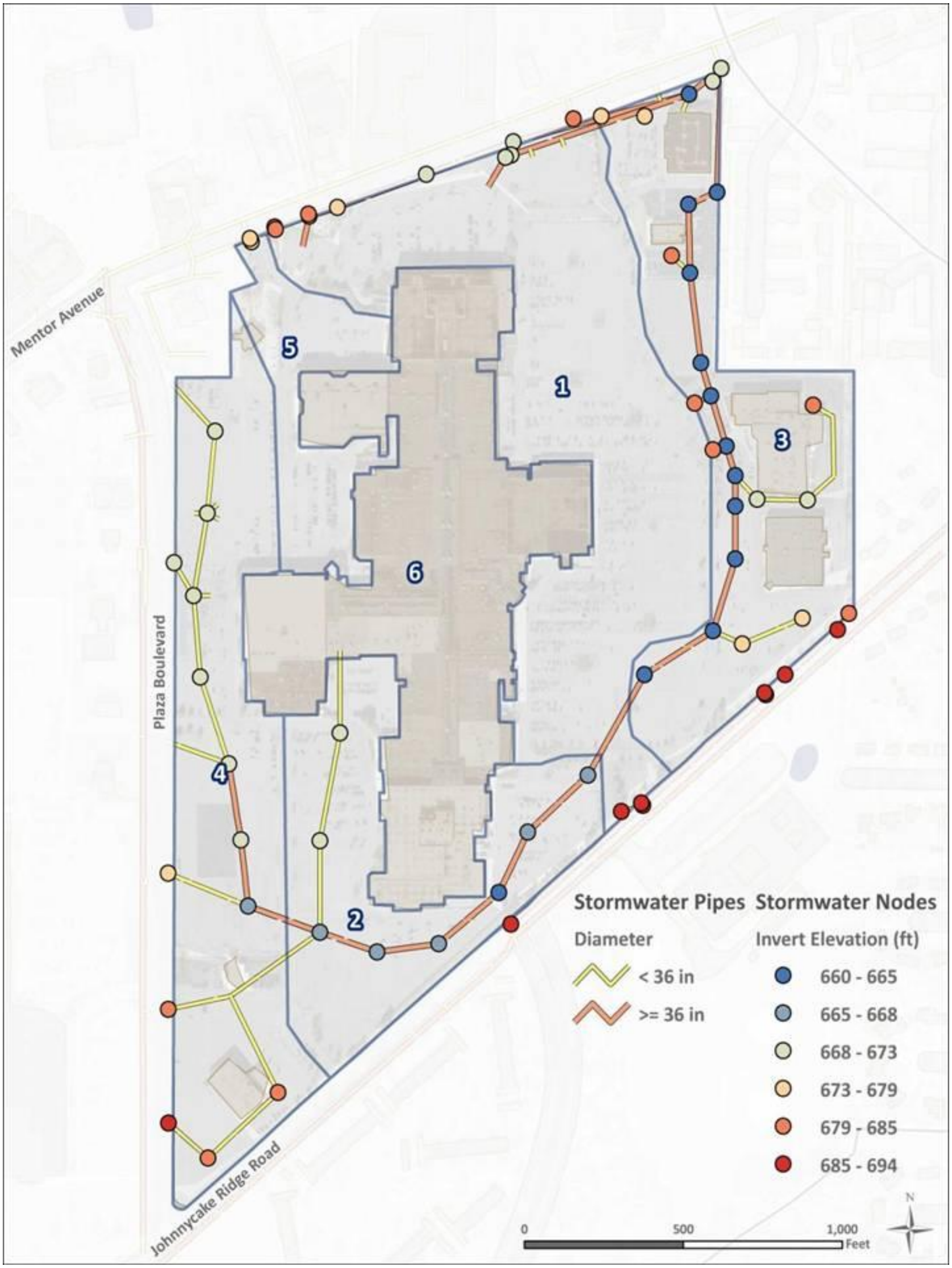


Figure 2-18. Detailed routing for GLM test area.

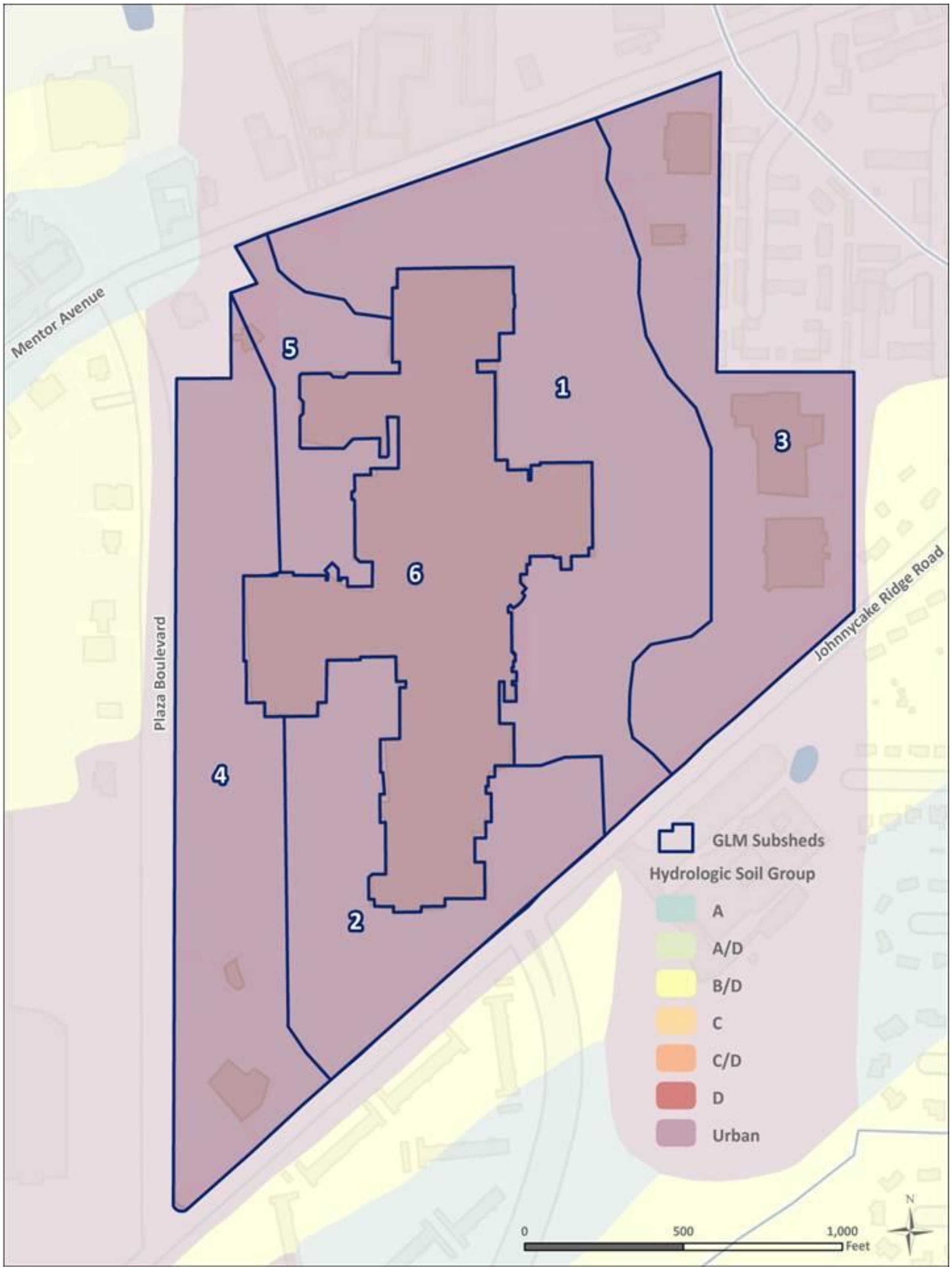


Figure 2-19. GLM test area HSGs.

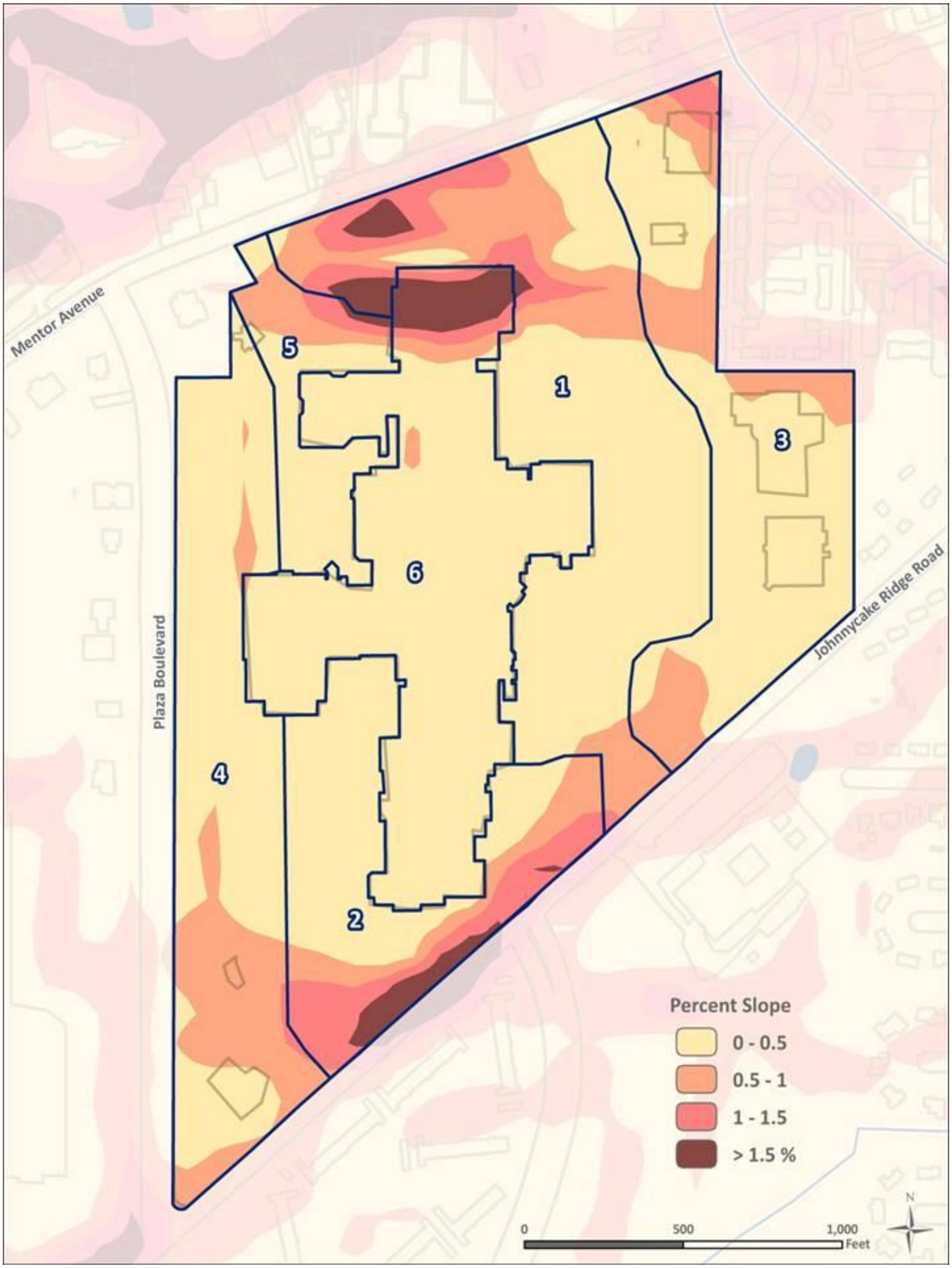


Figure 2-20. Surface slope analysis for GLM test area.

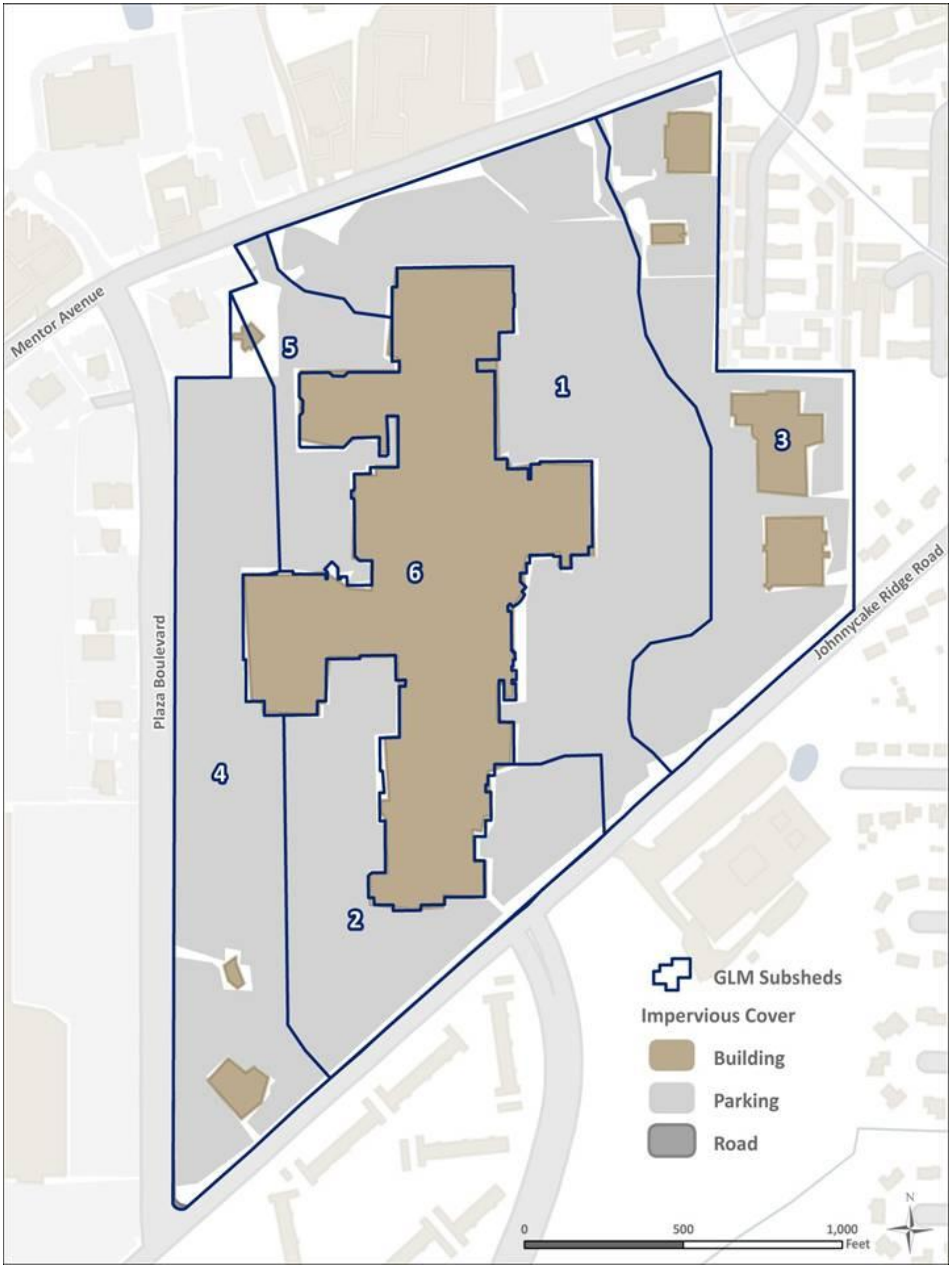


Figure 2-21. GLM test area impervious surfaces.

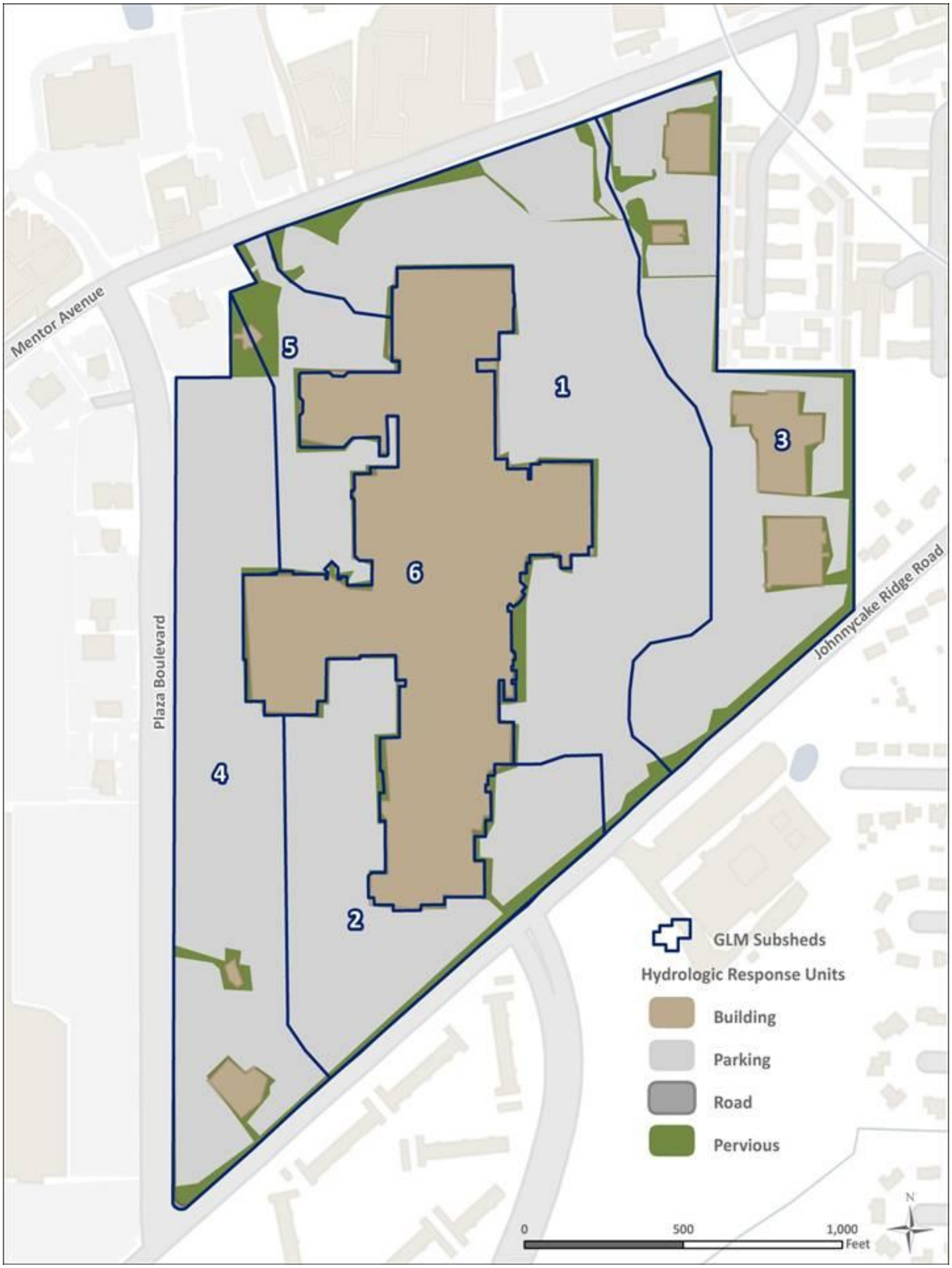


Figure 2-22. GLM test area HRUs.

2.2.3 Mentor Estates

The Mentor Estates test area is located in the City of Mentor and encompasses 218 acres of single family residential homes (Figure 2-23). Drainage from the test area is directly tributary to Ward / Newell Creek through one 66 inch outfall in the northwest corner of the subwatershed across from Hodgson Road. These two subdivisions were constructed between 1955 and 1980. There are currently no stormwater management facilities within the test area. However, it does receive upstream drainage from the Woodside Acres subdivision, which includes a large detention pond that outlets into Mentor Estates.

Most streets in the Mentor Estates subdivisions are curb and gutter configurations. Many of the roads also have sidewalks on both sides of the street with varying widths of green space between the sidewalk and back of curb. Several drainage improvement projects have been undertaken since 1970 that have converted rural section roads and roadside swales into curb and gutter. Approximately 60 percent of the roof drains in the test area are directly connected to the storm sewer system.

The test area contains 534 single family residential lots, averaging 0.40 acres in size. Lot sizes vary by location. The Shady Grove Estate subdivision lots are approximately 0.35 acres while corner lots in Mentor Estates are approximately around 0.8 acres. The average roof area is 1,970 square feet in size with average driveway area of 960 square feet. Residential street widths are approximately 24 feet, resulting in 15.7 acres of impervious areas associated with the roads (road length is 28,418 feet). The overall site is 24 percent impervious.

Soils within the test area are uniform consisting of HSG C/D poorly drained silt loam. Slopes are between zero and one percent. In order to represent Shady Grove Estates and Mentor Estates within *SUSTAIN*, the test area has been divided into three subwatersheds (Table 2-2 and Figure 2-24).

Table 2-2. Mentor Estates subwatersheds.

Subwatershed	Size *(acres)*	Flows to	Road Length *(ft)*	No. of Homes	Impervious Area *(acres)*		
					Road [1]	Roof [2]	Other [3]
1	32.1	2	3,074	91	1.69	4.12	2.01
2	99.8	Out	13,706	221	7.55	9.99	4.87
3	86.7	2	11,638	222	6.41	10.04	4.89
TOTAL	218.6		28,418	534	15.65	24.15	11.77

Notes:
1 Based on average road width of 24 feet
2 Based on average roof area of 1,970 square feet
3 Based on average driveway area of 960 square feet
4 Average front yard size assumed to be 3,000 square feet

Figure 2-23. Air photo of Mentor Estates test area.

Figure 2-24. Mentor Estates test area subwatersheds.

2.3 Five-step Process

Several activities included in this project support targeting and optimization. In particular, work plan tasks focus on the evaluation and design of stormwater BMPs (both structural and non-structural) that improve water quality conditions surrounding documented problems. A key objective is to prioritize source area and delivery mechanisms, in order to ensure effective use of available resources. The process used in this pilot effort to evaluate stormwater management opportunities involves five general steps. These include:

- ✓ Establish baseline conditions
- ✓ Identify BMPs to consider
- ✓ Evaluate opportunities and constraints
- ✓ Estimate costs
- ✓ Build targeting and optimization strategy

Figure 2-25 presents a general flow diagram of the process, identifying considerations and inputs. Basically, the process employed uses information on BMP effectiveness coupled with cost information to identify the most economical alternatives through an optimization step. The goal is to target specific implementation activities that address water quality problems related to stormwater.

Baseline Conditions. The initial step in evaluating and selecting BMPs to achieve stormwater management program goals is to understand baseline conditions. Identifying baseline conditions establishes a starting point from which improvements are made and progress is measured. Baseline conditions reflect the existing flow volume and / or pollutant loading from a stormwater source and provide a yardstick for measuring BMP effectiveness. For example, in TMDL implementation, baseline conditions are compared to the waste load allocation to determine the amount of pollutant load reduction or other changes needed.

Potential BMPs. Information about baseline conditions provides a benchmark that helps stormwater planners identify potential BMPs and / or combinations of BMPs to achieve overall program goals. In its simplest form, for example, the runoff volume produced by a certain design storm can be used to estimate detention needs. However, it is also important to understand other factors that might affect successful BMP implementation. These include environmental, physical, social, and political considerations. The goal of this step is to use baseline condition information coupled with local factors to generate a list of potential BMPs.

A task under this step includes inventorying existing BMPs to estimate current volume / pollutant reductions and identifying opportunities to maximize BMP performance. Understanding the existing suite of BMPs helps determine the type, quantity, and possible locations for additional BMPs to achieve progress toward implementation objectives.

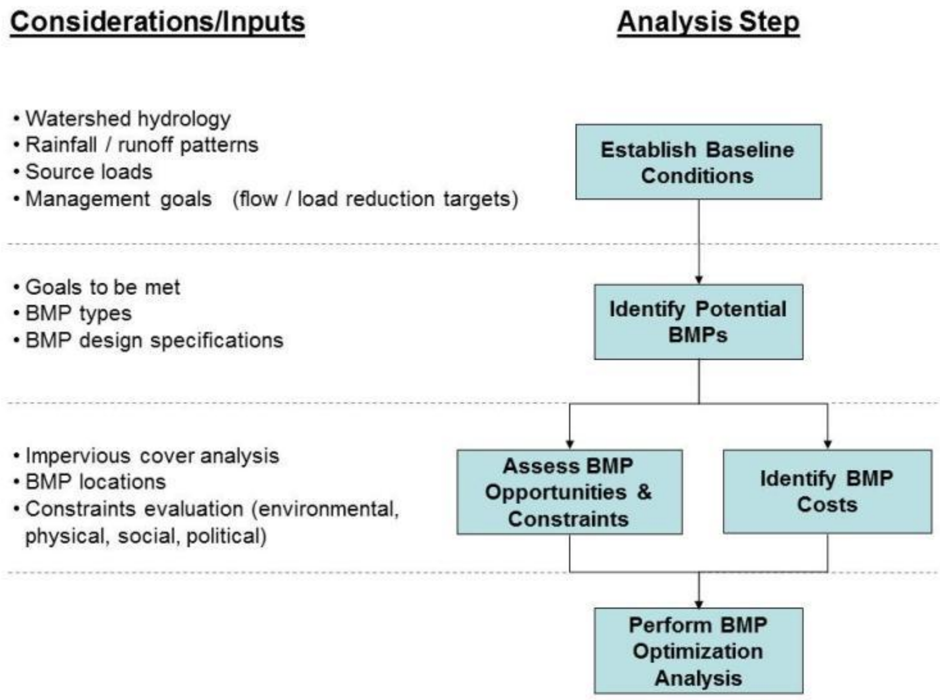


Figure 2-25. Process for BMP targeting and optimization.

Opportunities and Constraints. The goal of this step is to evaluate the list of potential BMPs and determine their overall performance at the watershed-scale. The intent is to identify options prior to selecting final BMP strategies. This involves examining the array of opportunities for placing identified BMPs in the subwatersheds or catchments of interest. Constraints (e.g., impervious cover types, soil infiltration rates, grading plans, local ordinances, social acceptance) are major considerations factored into this step.

Based on a comparison of the baseline conditions to watershed management goals, stormwater planners will have defined reduction targets. The baseline conditions analysis establishes the level of pollutant load reduction or other changes needed (e.g., reduction in peak flow, change in percent impervious area). Assessing configuration opportunities, stormwater planners can examine the expected performance of potential BMPs to help select those that will meet the goals identified in Step 1. Although challenging, this activity is essential to selecting BMPs with the most potential for making progress toward management objectives. For purposes of describing the overall process, this is discussed as a separate step after compiling the list of possible BMPs. However, stormwater planners can make assumptions about BMP opportunities and performance *while* generating the list.

Costs. Identifying BMP costs is an important undertaking for stormwater planners. Resource constraints can affect the number and type of BMPs that can be used to achieve progress toward program goals. At a minimum, stormwater planners should compare costs and expected pollutant reductions to ensure the final suite of BMPs will provide the most reductions for the least amount of money. For stormwater planners engaged in a more rigorous BMP optimization analysis, cost information on potential BMPs is essential for developing cost-effectiveness ratios (i.e., cost per unit of pollutant removed) to compare different BMPs for one type of land use or across several types of land uses.

Targeting and Optimization. A goal of targeting and optimization is to examine management strategies based on opportunities consistent with site suitability considerations. For example, slope and soil infiltration rates are key factors that affect successful performance of structural BMPs. At this stage, stormwater planners have identified the suite of feasible BMPs based on site-specific needs, goals, opportunities and constraints. Depending on the size of the planning area, the implementation goals and the resources available, there could be any number of combinations of BMP types and locations to meet goals.

To select the final BMP strategy, stormwater planners generally evaluate, prioritize or rank the potential BMPs based on relevant decision criteria, either qualitatively or quantitatively. Decision criteria likely include short-term and long-term costs, BMP performance, expected progress toward watershed goals, and compatibility with other planning priorities and objectives. Depending on the area and number of BMPs needed, a stormwater planner might use a qualitative evaluation of potential BMPs and targeted locations based on professional and local knowledge. Simple spreadsheet analysis could also be employed to identify the most appropriate and cost-effective scenario. While adaptive management can support the short-term implementation of priority BMPs with subsequent evaluation and modification, a stormwater planner tries to identify the most effective scenario first to minimize the need for additional BMPs and associated implementation costs. Therefore, the level of detail for the evaluation to select final BMPs can be driven by the benefit of the additional analyses compared to the potential costs to correct ineffective implementation.

3. Baseline Conditions

Effective implementation planning starts with a review of baseline conditions and watershed-scale factors that contribute to documented water quality problems in Ward / Newell Creek. In particular, a sound understanding of basic hydrologic processes at work in this watershed is the heart of stormwater management. Climate is the dominant driver of baseline conditions. A key component of protecting water resources is keeping the water cycle in balance (SEMCOG 2008).

The movement of rainfall from the atmosphere to the land, then back to the atmosphere, is a naturally continuous process. The balanced water cycle of precipitation, evapotranspiration, infiltration, groundwater recharge, and stream base flow is a key part of sustaining fragile water resources (Figure 3-1). A critical part of this analysis involves an assessment of rainfall patterns and watershed characteristics that affect the resultant runoff. Source areas and delivery mechanisms that will be the focus of targeted BMPs are driven by watershed response to precipitation. Describing the frequency and magnitude of rain events in conjunction with an analysis of associated runoff are key considerations in determining appropriate stormwater management strategies for Ward / Newell Creek.

Approximately 38 inches of precipitation falls on the Ward / Newell watershed each year, based on climate records collected from 1980 – 2010 at Painesville. This precipitation results in approximately 23 inches of runoff, based on USGS stream flow data for the Chagrin River during that same period. Although runoff at the Chagrin gage does not represent a completely undeveloped area, it does provide information that can be used to frame a discussion of baseline conditions for the Ward / Newell watershed. This includes a basic review of precipitation patterns and local factors that influence runoff.

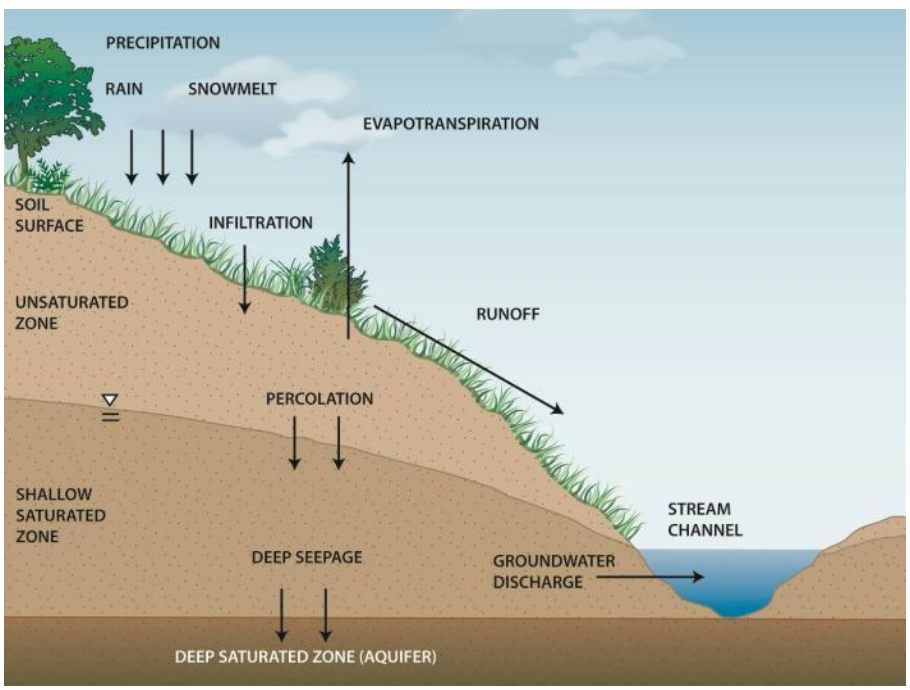


Figure 3-1. Water cycle.

3.1 Precipitation Patterns

Precipitation is clearly a significant factor to be considered in stormwater management. A major objective in developing effective management strategies and implementing LID practices is to keep as much stormwater on site as possible. Understanding rainfall patterns is a key part of identifying options. Annual variation, for example, is one consideration (as shown in Figure 3-2 for the Painesville climate station). Many BMPs are designed using storm frequency data (storm frequency is based on the statistical probability of a particular storm occurring in a given year). This information can be obtained through the National Weather Service (NWS) Precipitation Frequency Data Server (NWS 2004).

Recurrence intervals available on the server range from 1 to 100 years. This data is often used to address local stormwater regulations (e.g., Mentor) that include peak discharge control (Dorsey et al. 2009). The Critical Storm Method (CSM) provides one approach to examine peak discharge control needs. The CSM requires rainfall depth for the one through 100 years, 24-hour events. Table 3-1 summarizes rainfall depth – duration frequency information for the Painesville station.

Stormwater source inputs to receiving waters are ultimately a function of rainfall and snowmelt. Not all storms are equal; differences in frequency, magnitude, and duration play a major role in determining appropriate implementation strategies. Although large storms are critical in terms of flooding, most rainfall in the Mentor area actually occurs in relatively small storm events. An examination of precipitation patterns is a key part of stormwater implementation planning. This includes an analysis of rainfall intensity and timing to assess BMP performance relative to water quality goals.

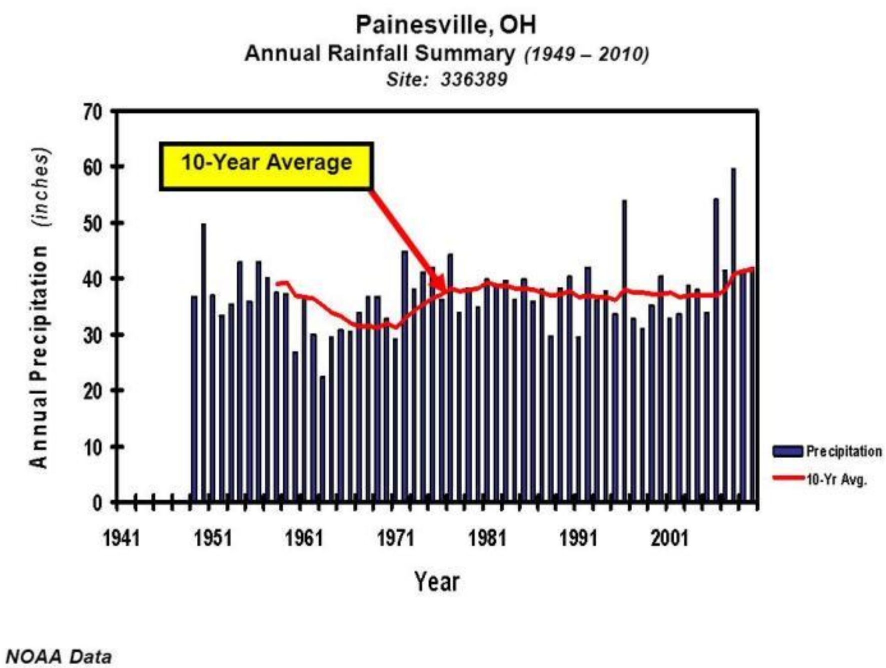


Figure 3-2. Annual precipitation summary for Painesville.

Table 3-1. Rainfall depth – duration frequency for Painesville.

Recurrence Interval *(years)*	Precipitation Frequency Estimates *(inches)*			
	Duration *(hours)*			
	3	**6**	**12**	**24**
1	1.15	1.37	1.62	1.96
2	1.38	1.64	1.94	2.35
5	1.76	2.07	2.42	2.94
10	2.06	2.43	2.84	3.42
25	2.48	2.96	3.45	4.12
50	2.83	3.41	3.96	4.69
100	3.19	3.89	4.53	5.29
	Data for Painesville retrieved from: http://hdsc.nws.noaa.gov/hdsc/pfds/			

While design storms provide a valuable long-term planning tool, the distribution of rainfall event depth is also an important factor. The effect of different rainfall patterns on runoff and stormwater source loads (and subsequent BMP performance) should be accounted for in the technical analysis. Figure 3-3 illustrates one method used to characterize rainfall distribution for the Painesville precipitation gage. As shown in Figure 3-3, 8.1 percent of measurable precipitation events in Painesville exceed Ohio's WQv benchmark (e.g., 0.75 inches over a 24-hour period).

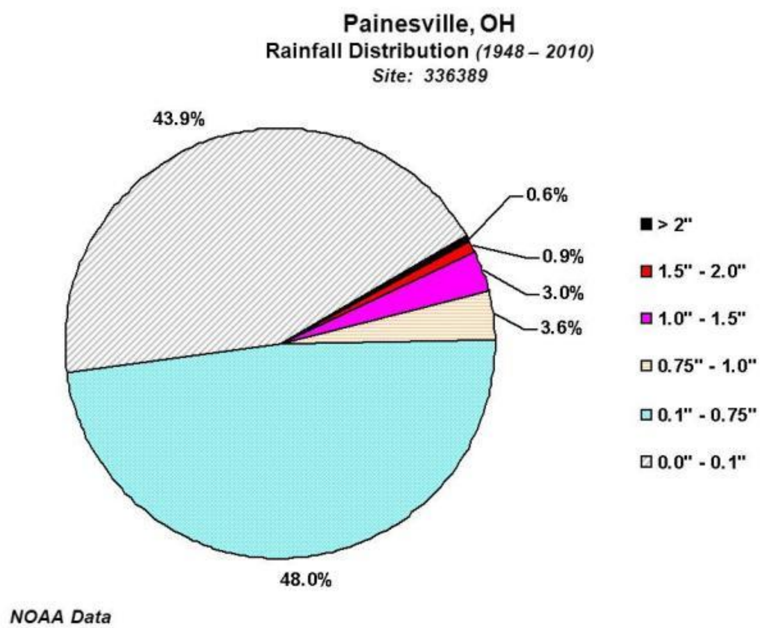


Figure 3-3. Rainfall distribution for Painesville.

State and local agencies often define critical event rainfall depths in the stormwater management manuals or ordinances. For example, Ohio's WQv establishes a metric that guides design of post-construction BMPs (e.g., filtration, infiltration, detention) to achieve targets for volume and peak rate controls. In

Ohio, the WQv has two protection objectives: reducing the pollutants suspended in runoff and reducing the energy of common storm events responsible for most channel erosion (Ohio DNR 2006).

Basically, WQv represents the critical event used to calculate stormwater quantity and quality impacts of new development and redevelopment. In Ohio, WQv is the volume that results from a 0.75 inch event over a 24-hour period. The choice of 0.75 inches as the WQv rainfall capture depth and the requirement that the extended detention (24 - 48 hour) drawdown come from a *brimful* condition allows this single requirement to function both as a water quality requirement and a channel protection requirement. In essence, the WQv sizing and drawdown requirements result in capture, extended detention and treatment of routed rainfall depths of between 0.85 and 1.5 inches (Dorsey et al. 2009).

The water quality volume is calculated using the following equation, adapted from *Urban Runoff Quality Management* (ASCE / WEF 1998):

$$WQv = C * P * (A/12)$$

where:

C = runoff coefficient

$= 0.858 * i^3 - 0.78 * i^2 + 0.774 * i + 0.04$

i = watershed imperviousness ratio (percentage divided by 100)

P = 0.75 = amount of precipitation occurring in a 24-hour period (inches)

A = area treated by the BMP(s) (acres)

Source loads associated with many small storms can be equally important in terms of their effect on receiving streams. In the case of Painesville, 91.9 percent of the measureable precipitation events are at or below WQv. For instance, there may be a critical precipitation depth where measurable stormwater loads begin to occur, depending on subwatershed characteristics. From this perspective, BMP targeting and optimization efforts should examine issues such as the full range of flows associated with all storms, as well as flows associated with the design storms such as WQv.

Related to the identification of design storms, it is useful to examine the cumulative frequency distribution of 24-hour precipitation events. A frequency distribution of daily precipitation data can be viewed in several ways (Figure 3-4). The first is to determine the frequency interval by considering all days (whether or not there was measurable precipitation), as shown by the lower curve in Figure 3-4. This approach allows for comparison with flow duration curves because daily precipitation values are sorted from high to low; the total number of days is used to calculate to recurrence percentage.

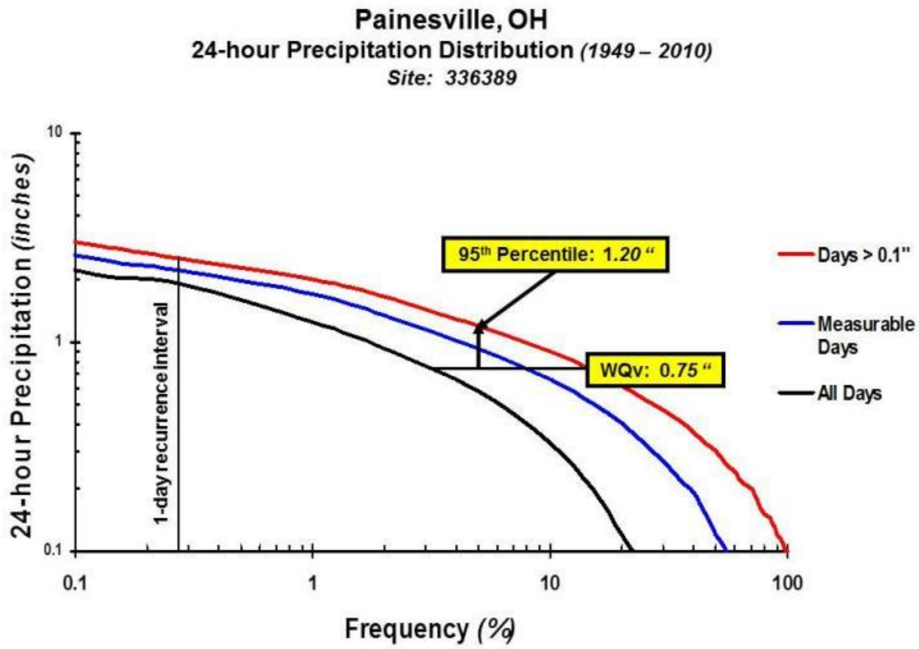


Figure 3-4. Cumulative frequency distribution of 24-hour precipitation events for Painesville.

Over the past few years, there has been an increased emphasis on volume-based hydrology in stormwater management (Reese 2009). The premise is that reductions in stormwater volume will lead to reductions in pollutant loading (National Research Council 2008). USEPA technical guidance has identified using the 95th percentile rainfall event as one option to meet stormwater runoff reduction requirements for Federal facilities (USEPA 2009). The 95th percentile storm is calculated through the use of a frequency distribution of all daily rainfall values with small precipitation events removed (i.e., those less than 0.1 inches). This design volume captures all but the largest five percent of storms, as depicted by the upper curve in Figure 3-4. For the Painesville gage, this corresponds to 1.20 inches.

3.2 Hydrology

The hydrology of the Ward / Newell Creek watershed is driven by local climate conditions. This includes situations that often result in flashy flows, where the stream responds to and recovers from precipitation events relatively quickly. Limited flow data makes it difficult to describe the full range of hydrologic conditions the Ward / Newell Creek watershed may experience. Although long term stream gaging has not been conducted on Ward / Newell Creek, the USGS has monitored flow in the Chagrin River at Willoughby.

Figure 3-5 and Figure 3-6 show rainfall runoff patterns over a six-month period with data from the Painesville precipitation station and the USGS Chagrin flow gage. This time frame is used because Ohio EPA installed a level logger on lower Ward-Newell Creek in April 2011. The level logger monitoring effort was in conjunction with work on the lower Grand River to gather information on small watershed runoff patterns in the Mentor – Painesville area.

Flow duration curves are an effective method to characterize hydrologic conditions and are an important component of an overall hydrologic analysis. Duration curves provide a quantitative summary that represents the full range of flow conditions, including both magnitude and frequency of occurrence

(USEPA 2007). Development of a flow duration curve is typically based on daily average stream discharge data. A typical curve runs from high flows to low flows along the x-axis, as illustrated in Figure 3-7.

This graph depicts flow duration curves for Ward-Newell Creek compared to the Chagrin gage. These duration curves shown in Figure 3-7 are expressed as unit area flows (i.e., inches per day) for direct comparison between sites. Note the flow duration interval of forty associated with a stream discharge of 1.92 cfs per square mile (i.e., forty percent of all observed stream discharge values equal or exceed 1.92 cfs per square mile).

It is worth noting that the 2011 Ward-Newell unit area duration curve is reasonably close to the one for the Chagrin River developed using flows measured on exact same days. The 2011 curves are also shown with one developed for the Chagrin River using the full record. This comparison highlights the pronounced effect that a wet year has on flows (precipitation in this area set records in 2011).

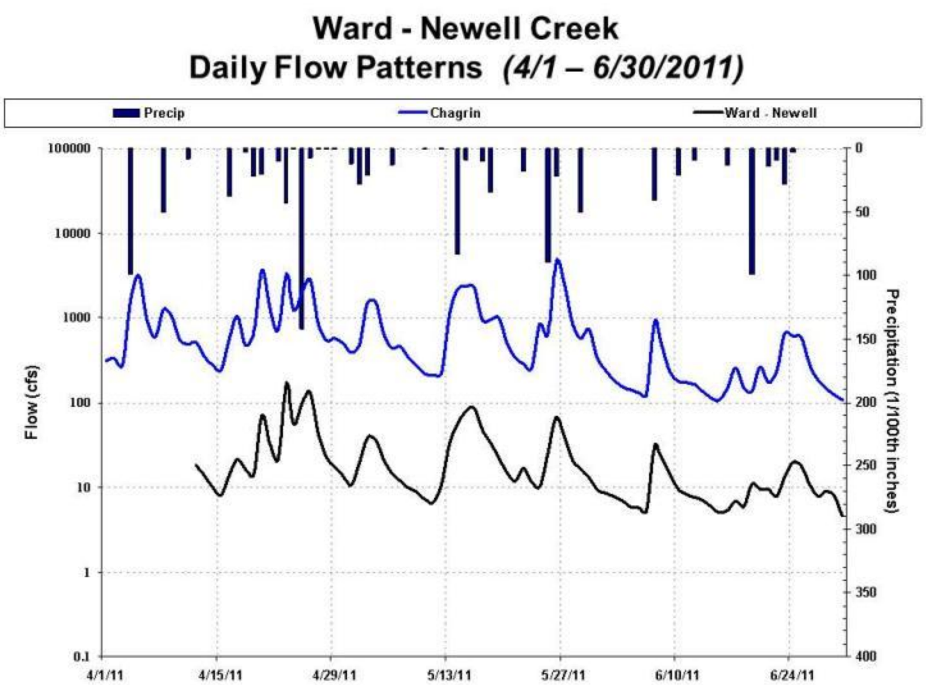


Figure 3-5. Chagrin watershed rainfall – runoff patterns (April – June 2011).

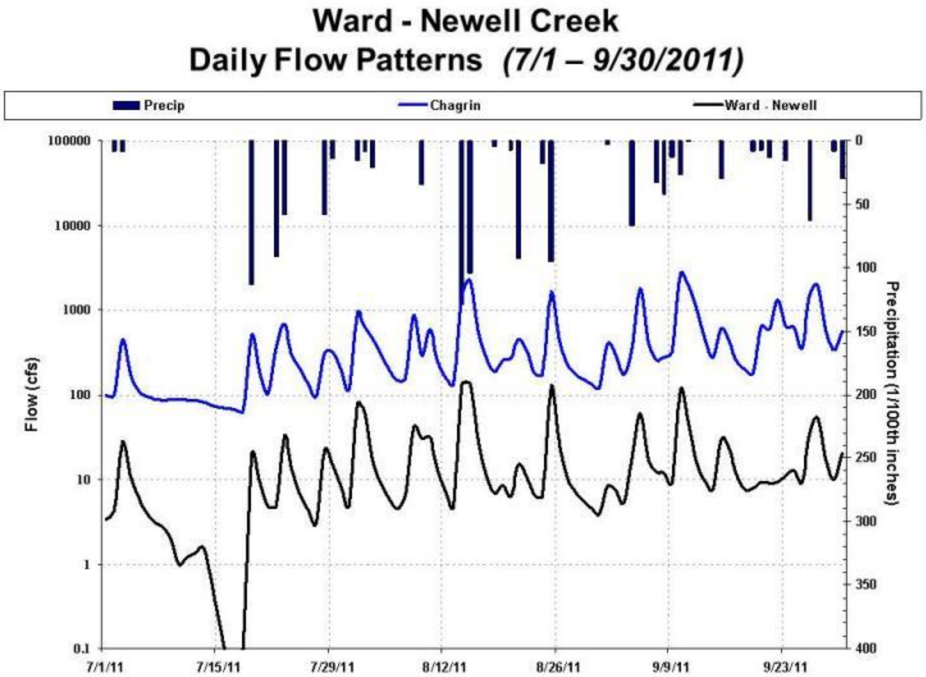


Figure 3-6. Chagrin watershed rainfall – runoff patterns (July – September 2011).

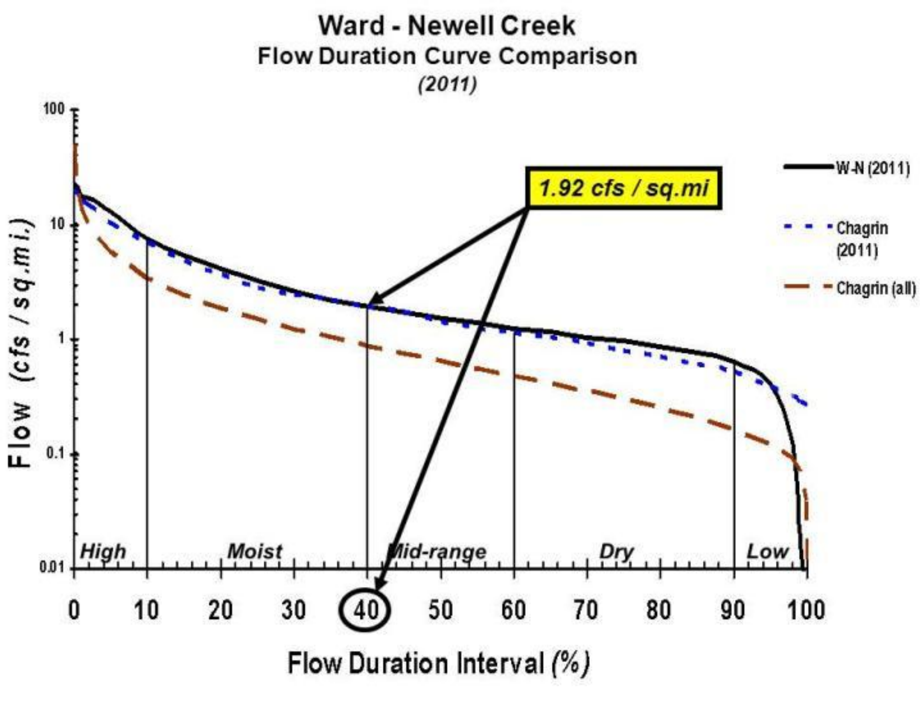


Figure 3-7. Unit area flow duration curve for Ward-Newell Creek.

3.3 Runoff Models

Watershed response to precipitation events is an equally important part of BMP targeting and implementation. While rainfall and snowmelt act as driving forces, the resultant runoff serves as a key focal point for stormwater management programs. Hydrologic measures such as total runoff volume, peak flow rate, runoff hydrograph, and duration curves are often used to guide the design of protection, control, and restoration strategies associated with stormwater management.

A key objective of analyzing runoff patterns is to prioritize source area and delivery points / mechanisms to help ensure effective BMP targeting. Figure 3-8 illustrates the utility of flow duration curves in assessing the effects of land use change on watershed hydrology. In this example, land use changed dramatically from 1950 to 1984. The conversion from low density to high density residential increased both the magnitude and frequency of high flow events. As discussed earlier, implementation of LID practices strive to minimize the effect of altered hydrology.

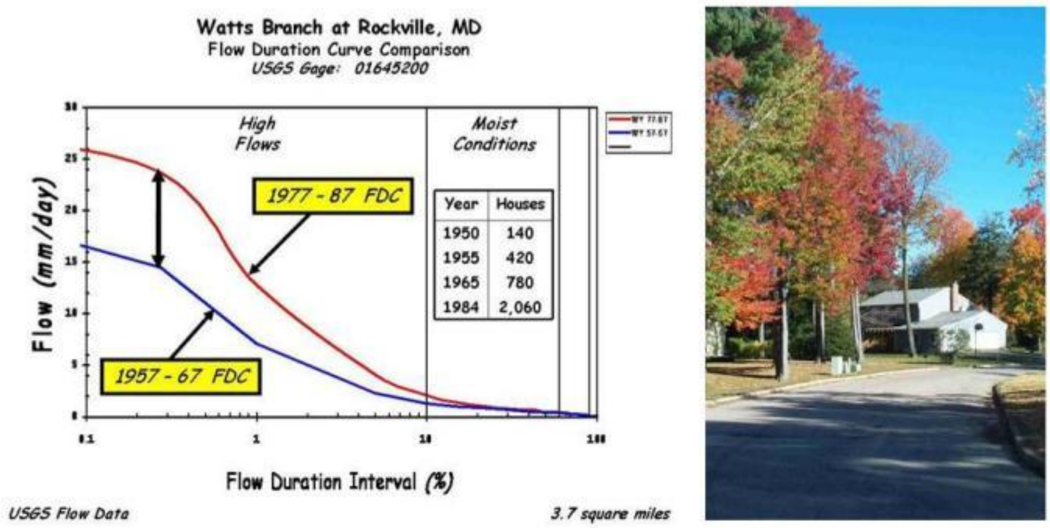


Figure 3-8. Effect of land use change on flow duration curve.

Ideally, real time, fine scale monitoring of stream flow and water quality could guide the design of BMP implementation strategies. However, the costs associated with this level of data collection are generally much greater than available resources. For this reason, computer models are often used to develop information that describes watershed response to precipitation events.

Figure 3-9 illustrates a simple conceptualization of the relationship between rainfall – runoff models and their use in assessing BMPs. In this hypothetical scenario, rain falls on the land producing runoff (depicted by the LAND box). The resultant runoff is routed to the stormwater BMP for subsequent evaluation of its performance.

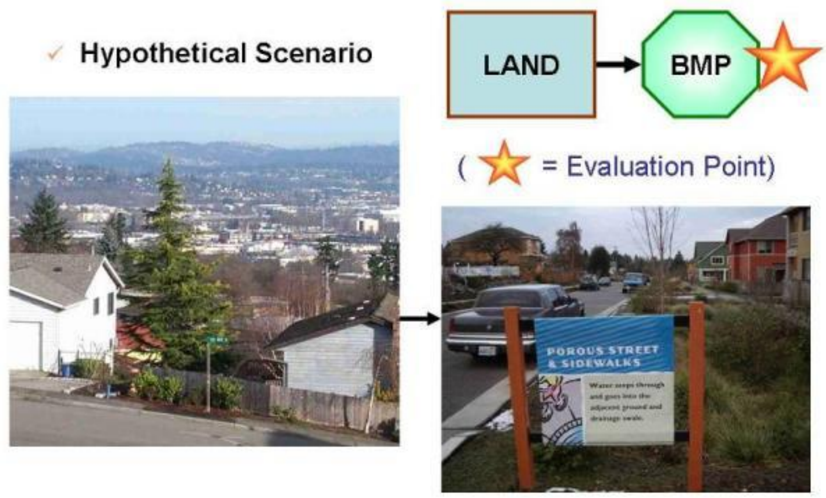


Figure 3-9. Stormwater modeling concepts.

There is a wide variety of models available that have been used to assistance stormwater management activities in describing runoff patterns. Similarly, the approaches range from simple to complex, and include:

- ✓ Storm Water Management Model (SWMM)
- ✓ Hydrologic Simulation Package FORTRAN (HSPF)
- ✓ LSPC
- ✓ P8 Urban Catchment Model (P8-UCM)
- ✓ Source Loading and Management Model (SLAMM)
- ✓ HEC Hydrologic Modeling System (HEC-HMS)
- ✓ SCS / NRCS Win TR-20 and Win TR-55

This above list is by no means complete. However, it does reflect the most common models used to address urban runoff concerns.

3.3.1 Hydrologic Response Units

One of the most significant technical challenges in the targeting and optimization process is connecting watershed runoff information to a BMP assessment framework. A technique being used in conjunction with rainfall – runoff modeling to address stormwater concerns is the use of HRUs. Example applications of this method include project work in Vermont, the Charles River, and Los Angeles County. Dominant factors considered include land use, soil type, and slope.

In a watershed model, land unit representation is sensitive to the features of the landscape that most affect hydrology. Important features include surface cover, soils, and slope. In urban settings, it is important to estimate the division of land use into pervious and impervious components. When HSG are not homogenous in a watershed, further subdividing pervious land cover according to HSG can provide a higher degree of resolution. Slope might also be an important factor in some areas, particularly where it varies noticeably. For the Ward / Newell Creek pilot effort, the combination of HSG, slope, and impervious surface cover (road, parking and rooftop) were considered in the definition of HRUs.

Hydrologic Soil Group. GIS data sets of HSG provided by CRWP were used to identify the infiltration potential of soils. HSGs are used to classify the infiltration capacity of soils, rating them as either class A, B, C or D. HSG A has the highest infiltration potential, while D has the lowest. Unknown and predominately urban soil types are also identified.

Surface Slope. A 10 meter resolution digital elevation model provided by CRWP was used to evaluate the distribution of surface slope within the Ward / Newell watershed. The digital elevation model was processed using ESRI ArcDesktop 9.3.1 and the Spatial Analyst extension to derive a second raster representing percent slope throughout the test areas. Analysis of the distribution of slopes within the pilot areas reveals that the values range only between zero and one percent suggesting that the site is extremely flat. Areas that show slopes greater than 1.5 percent appear to be influenced by buildings or other structures on the site. For these reasons, slope was excluded from the final HRU development.

Impervious Surface Type. GIS data sets of impervious surfaces provided by CRWP were used. The impervious surfaces were classified as either roads, parking lots, or building rooftops based on existing attributes saved in the shape file. Those three feature types were merged into a single raster representation while preserving the distinction between types of impervious cover.

An overlay of soil and impervious surface type was performed using the GIS raster layers. Impervious surfaces were given priority in the overlay, meaning that only areas not already marked as impervious were considered pervious. As discussed, the slope raster was excluded from development of HRUs. This overlay resulted in a distribution of five unique HRU categories that capture the physical texture of the subwatersheds. Three HRU categories represent unique impervious surfaces: roof top, road way, and parking areas. The other two HRUs represent pervious surfaces: one for A/B soil types and one for C/D soils.

3.3.2 Rainfall – Runoff Time Series

A rainfall – runoff time series was generated for each HRU. The Loading Simulation Program C++ (LSPC) was used to provide initial estimates. LSPC is a re-coded version of the HSPF watershed model. One objective of the overall pilot effort is to identify challenges associated with using *SUSTAIN*. In the case of the Ward-Newell pilot effort, long-term flow records were not available for watershed model calibration and validation. In order to examine the effect of watershed modeling on the overall BMP targeting and optimization process, SWMM was also used to provide a comparison of results.

One objective of GI and low impact development (LID) practices is to mitigate the adverse effects of impervious surfaces. For that reason, it is useful to examine WQv. Quantifying the runoff associated with a site or area, then comparing it to WQv provides a general context for reduction estimate calculations. It also gives a frame of reference relative to permit requirements in Ohio. Figure 3-10 visually describes the relationship between the runoff volume produced by a 24-hour 0.75 inch event and the effective impervious area. This graph illustrates the volume associated with parking surfaces in the GLM test area.

This simple analysis demonstrates the benefit of decreasing the amount of impervious surface in terms of total runoff volume reduction. The next aspect of the screening analysis expands the assessment by examining a sequence of rain events and subsequent runoff produced. This is accomplished through the use of the rainfall – runoff model LSPC. Figure 3-11 shows rainfall patterns and expected site runoff volumes for a portion of the GLM test area (sub-shed 4) using hourly precipitation data from the Painesville climate station.

The time period shown in Figure 3-11 is on the warmer portion of 2006 (April 1 to October 31). Runoff volumes during these months are typically in response to rain events (as opposed to snow melt generated stormwater). Figure 3-11 also depicts WQv, showing the frequency that the value is exceeded. The total runoff volume during the period depicted in Figure 3-11 is approximately 2.34 million cubic feet. This volume provides a benchmark against which various reduction control strategies and assumptions can be compared.

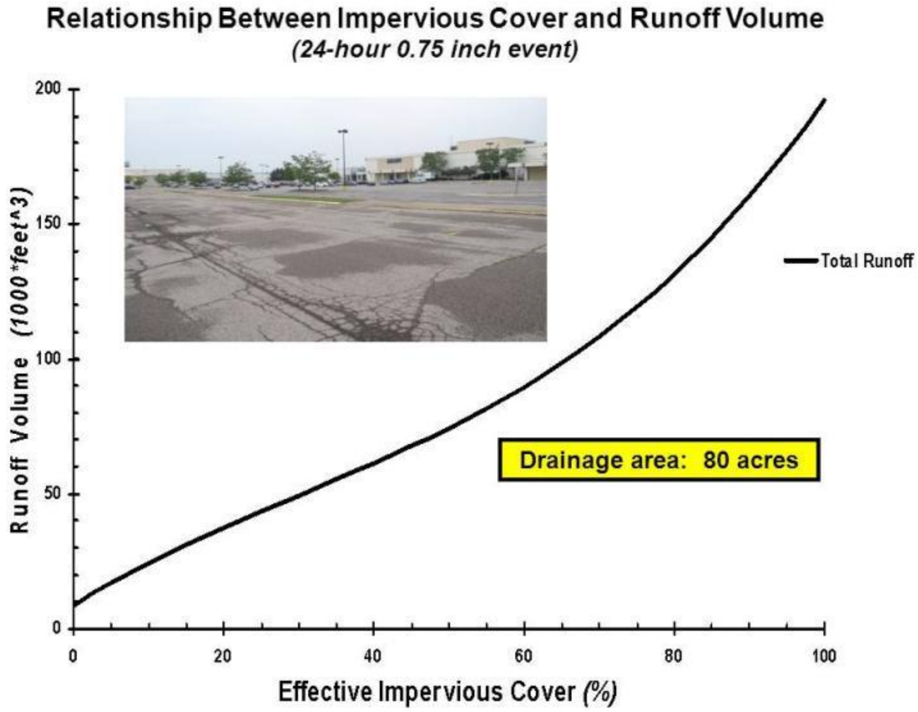


Figure 3-10. Relationship between WQv and effective impervious surface.

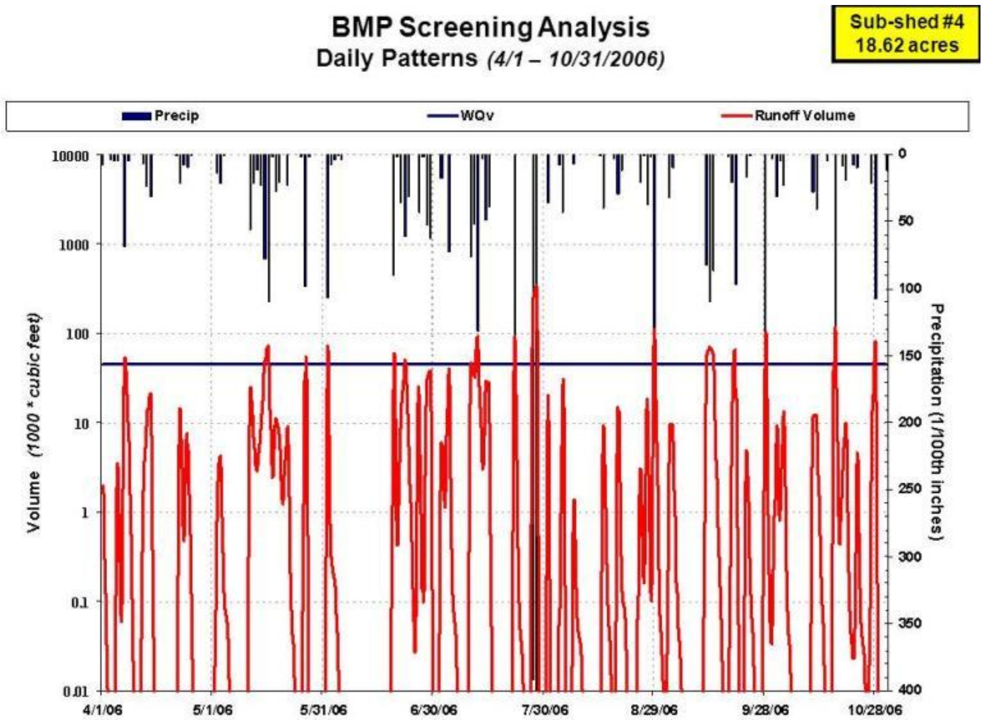


Figure 3-11. Rainfall – runoff volume for subwatershed 1 (April – October 2006).

4. BMPs Considered

Examples of the stormwater management practices that can be assessed with *SUSTAIN* include bioretention, rain barrels, cisterns, detention ponds, infiltration trenches, vegetative swales, porous pavement, and green roofs. However, not all BMPs are equally suitable to all site conditions and performance goals across watersheds. Consequently, several important site-specific factors were considered when identifying those BMPs to include in the project analysis. This section presents a brief overview describing the general representation of practices within *SUSTAIN*. An assessment of BMP opportunities within the test area is provided following that discussion.

The BMP module within *SUSTAIN* is designed to provide a process-based simulation of flow and pollutant transport routing for a wide range of structural practices. The BMP module performs the following hydrologic processes to reduce land runoff volume and attenuate peak flows: evaporation of standing surface water, infiltration of ponded water into the soil media, deep percolation of infiltrated water into groundwater, and outflow through weir or orifice control structures. A simplified schematic of the BMP simulation process is included in the *SUSTAIN* manual and is shown in Figure 4-1.

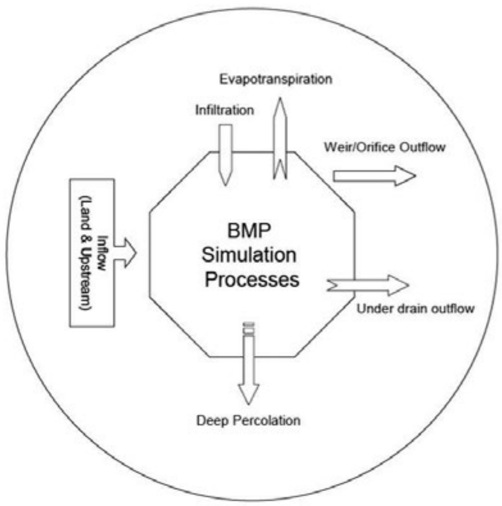
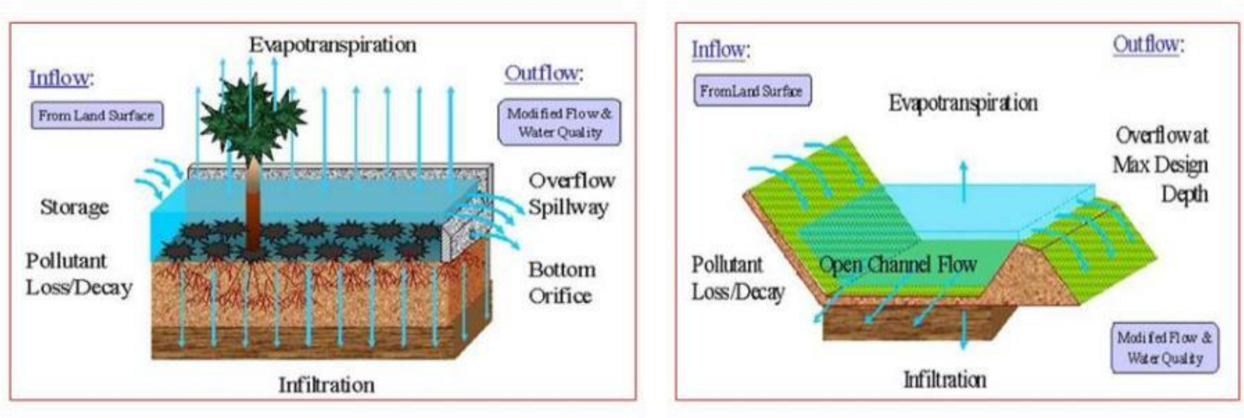


Figure 4-1. BMP simulation processes.

Urban stormwater BMPs in *SUSTAIN* are simulated according to a set of design specifications using a unit-process parameter-based approach (Figure 4-2). This has many advantages over most other modeling tools, which simply assign a single percent effectiveness value to each type of practice. Overall BMP performance in *SUSTAIN* is a function of its physical configuration, storm size and associated runoff intensity and volume, and moisture conditions in the BMP.

A general estimate of BMP performance can be developed for each practice being considered. One way to view this information is in in terms of sizing. Sizing of BMPs is typically focused on capturing a certain depth of runoff (e.g., WQv). Curves can be developed that show the performance of a BMP over a long-term period (rather than as a single storm or design storm event. This is an important aspect of the BMP opportunity assessment. Inherently, assumptions must be made when transitioning from a location specific analysis (e.g., site-scale) to an evaluation of larger areas, such as the neighborhood- or watershed-scale (Figure 4-3).



Storage / Infiltration BMPs **Channelized BMPs**

Figure 4-2. Major processes included in BMPs.

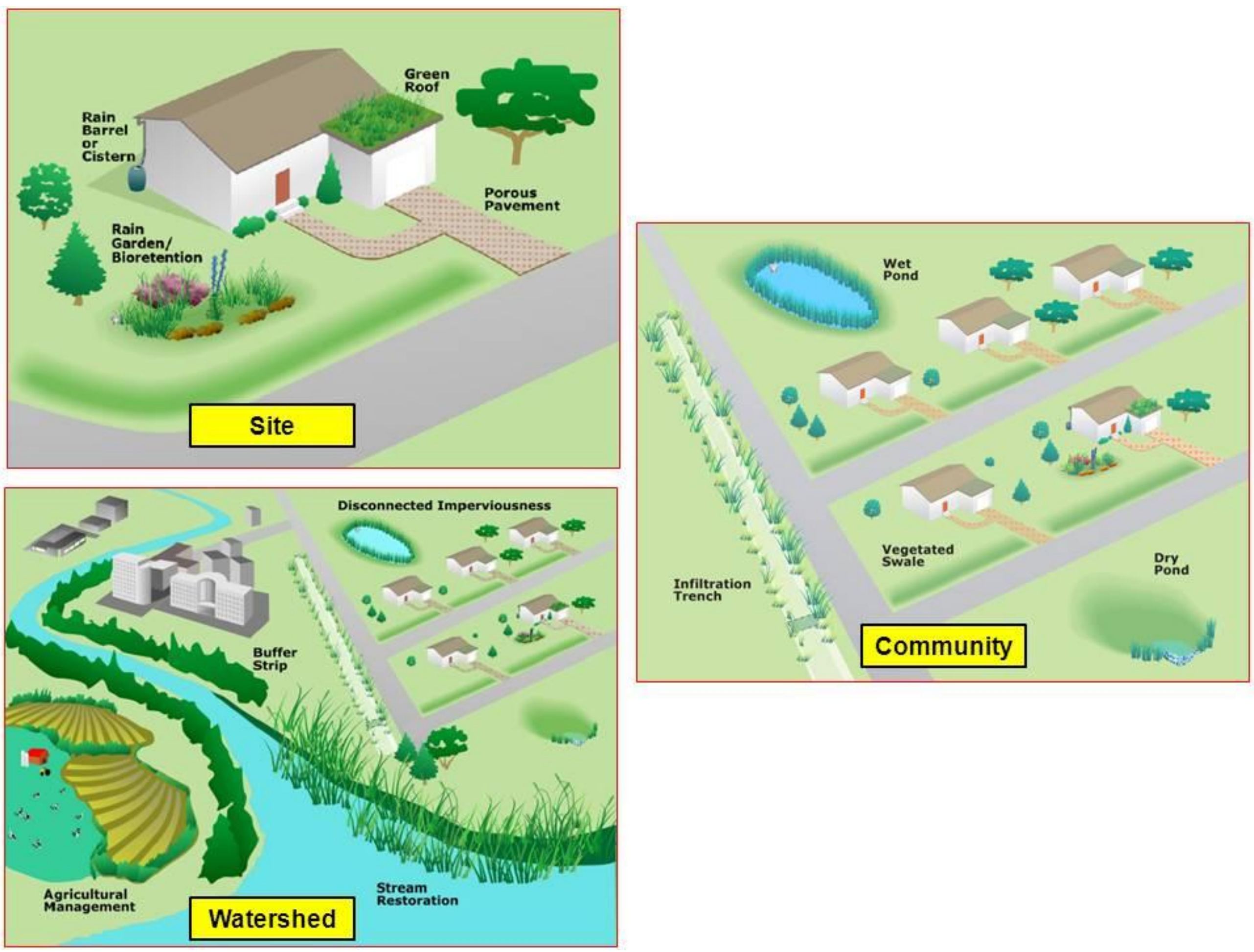


Figure 4-3. BMP assessment scales.

Figure 4-4 shows an example performance curve for a BMP of interest in this pilot effort: bioretention. One benefit of developing these curves is that they illustrate the sensitivity of BMP performance to the range of key variable (e.g., infiltration rates, storage depth, etc.). The curves also provide a way to quantify uncertainty regarding assumptions. In addition, the performance curves highlight those design parameters that are most important when developing specifications for implementation projects. Several example key design parameters that can be varied in *SUSTAIN* for bioretention are listed in Table 4-1. Finally, the curves can help guide decisions where cost trade-offs are involved (e.g., size of area to treat, amount of amendment material to promote greater infiltration, underdrain system design, etc).

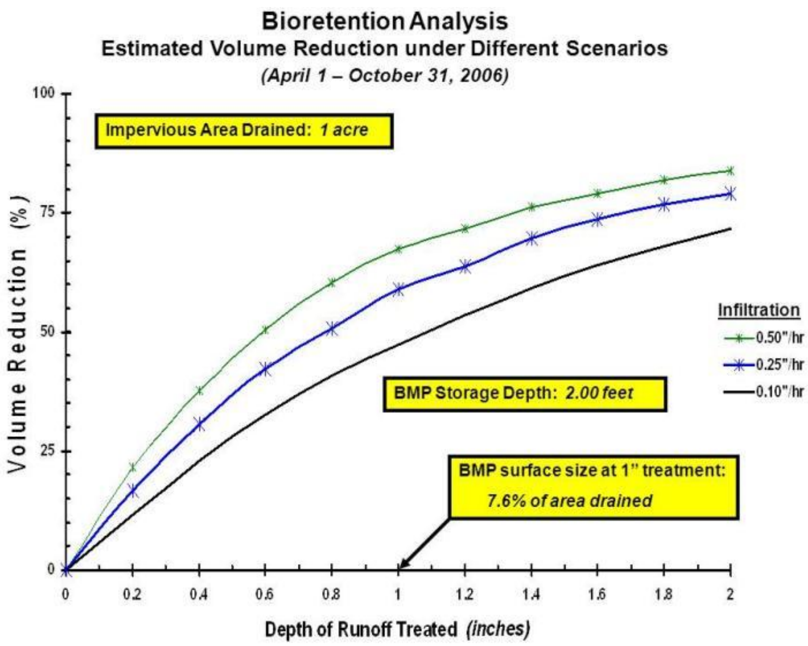


Figure 4-4. General BMP performance curve -- bioretention.

Table 4-1. Example key BMP design parameters -- bioretention.

Dimensions	
• Length *(feet)* • Width *(feet)*	• Design drainage area *(acre)*
• Ponding depth defined through one of following options: ✓ Orifice height *(feet)* ✓ Weir height *(feet)*	
Substrate Properties	
• Depth of soil *(feet)* • Soil porosity *(0 - 1)* • Soil field capacity	• Soil wilting point • Vegetative parameter A • Soil layer infiltration *(inches / hour)*
• Underdrain structure *(if applicable)* ○ Storage depth *(feet)* ○ Media void fraction *(0 - 1)*	○ Background infiltration *(inches / hour)*

With respect to the Chagrin pilot, significant differences exist between the two test areas (e.g., soil types, land use). These factors can be major determinants relative to specific types of BMPs to include in the analysis. The GLM, for example, is completely dominated by commercial land use. The primary stormwater source area of concern is 80 acres of parking lot. Soils differ from the Mentor Estates area in that the mall complex is situated on a dunal ridge that has greater infiltration capacity. CRWP, in consultation with the City of Mentor, identified three major categories of BMPs to examine at this location: bioretention, infiltration trench, and pervious pavement.

In contrast, the Mentor Estates area (along with much of the remaining Ward / Newell watershed) contains soils with relatively low permeability and is susceptible to a high water table. Infiltration basins and trenches were not considered among the suite of applicable practices for this subwatershed. There is also very limited potential use of green roofs and cisterns in this area due to the type of land use and buildings within the subdivision. Consequently, these practices were also not considered in the Mentor Estates analysis.

Bioretention areas were chosen to be represented in place of vegetated swales because, in practice, they typically provide more volume control. Vegetated swales are modeled primarily as conveyance systems in *SUSTAIN* and provide little volume control or water quality treatment. Wetlands were also not modeled because the goal of optimization is volume control, and wetlands are not primarily used for that purpose. The following BMPs were identified as applicable to the pilot study sites:

- Bioretention (rain garden, bioswale, and bioretention)
- Pervious pavement
- Infiltration trench (GLM only)
- Rain barrels in series with rain gardens
- Detention pond

Each of those practices was evaluated for applicability in the watershed on the basis of a review of aerial imagery, site and grading plans, field reconnaissance, and acceptability. Candidate locations were selected according to available land area and proximity to sources of runoff and pollutants.

The assessment of BMP opportunities also involved analyzing various combinations of practices (i.e., treatment trains). Using a treatment train approach, stormwater management begins with simple methods that minimize the amount of runoff that occurs from a site. Typically those practices involve either on-site interception (e.g., rain barrels) or on-site treatment (e.g., bioretention, pervious pavement).

The following sections provide a description of each BMP and the considerations made during the applicability analysis. Modeled design specifications for each practice are described in Section 5.

4.1 Bioretention

Bioretention practices are stormwater basins that utilize a soil media, mulch, and vegetation to treat runoff and improve water quality for small drainage areas (Ohio DNR 2006). A bioretention area consists of a depression that allows shallow ponding of runoff and gradual percolation through a soil media or uptake by vegetation. Water that percolates then either infiltrates through undisturbed soils or enters a storm sewer system through an underdrain system.

Bioretention is able to attenuate flow and reduce volume. These BMPs use biological, chemical, and physical processes to remove a variety of pollutants. Bioretention is generally applicable to small drainage areas, is good for highly impervious areas, and provides an option for retrofit situations. Bioretention can be a landscape feature and has relatively low maintenance requirements.

Numerous design applications exist for bioretention. These include use in residential lots, on commercial / industrial sites (Figure 4-5), as off-line facilities adjacent to parking lots, and along highways and roads. Bioretention practices are typically sized for common storm events (e.g., WQv).

4.1.1 Rain Gardens

Rain garden areas are assumed to be located in front yards of residential areas and are designed to serve the overflow from rain barrels and runoff from the surrounding area in Mentor Estates subwatershed 3. Driveways are routed to rain gardens through a trench drain at the bottom of the driveway, thereby capturing this impervious area prior to discharging into the road. Rain gardens are assumed to be constructed and maintained by the homeowner with little costs associated with design.

A two foot soil amendment is assumed, with no underdrain. Front yard size was considered when setting the upper limit on the area of the bioretention practices (200 square feet). It is assumed that a maximum of 25 percent of homes in the residential area could be served by rain gardens in combination with a rain barrel. A total of 12.5 acres (2.5 impervious and 3.8 pervious acres) could be treated by rain gardens.

Figure 4-5. Chagrin area rain garden.

4.1.2 Bioswales

A bioswale is a modified swale that uses bioretention media to improve water quality, reduce the runoff volume, and modulate the peak runoff rate while also providing conveyance of excess runoff. Bioswales are well suited for use within the rights-of-way of linear transportation corridors. They perform the same functions as grassed swales by serving as a conveyance structure and filtering and infiltrating runoff. Because bioretention media is used, they provide enhanced infiltration, water retention, and pollutant removal. Runoff reduction is achieved by infiltration and retention in the soils and interception, uptake, and evapotranspiration by the plants. Removal of pollutants has been positively linked to the length of time that the stormwater remains in contact with the herbaceous materials and soils (Colwell 2000).

Within the Chagrin watershed, bioswales have been installed along Sterncrest Road (a residential road in Orange Village) as an alternative method to managing chronic flooding problems. The bioswales were designed to receive stormwater runoff from the adjacent roadway and overland runoff from the residential area (Figure 4-6).

Figure 4-6. Chagrin area bioswale along Sterncrest Road.

Bioswales are linear features that are designed to provide off-line retention for road runoff and surrounding areas. Potential locations for bioswales in residential areas were identified through aerial imagery analysis and evaluation of grading and utility plans. It is assumed that bioswales could be installed along 90 percent of the roadways in the western watershed where sufficient width of green space exists between the curb and sidewalk.

Bioswales are assumed to be up to five feet in width encompassing up to 0.64 acres of the watershed with one-half foot of ponded depth. A 36 inch soil amendment is assumed. A similarly designed and constructed site is present in the City of Toledo along Maywood Avenue. The practices are represented in the model similarly to rain gardens and treat up to 5.8 acres of impervious and 6.6 acres of pervious surfaces in Mentor Estates subwatershed 1.

4.1.3 Bioretention Facilities

Bioretention facilities are typically larger rain gardens with underdrains and in this case are designed to capture and retain runoff from roads, driveways, and the front half of all parcels in Mentor Estates subwatershed 2. Potential locations for bioretention in subwatershed 2 were identified through aerial imagery analysis. Bioretention facilities are sized according to the available land area adjacent to the roads and are assumed to be up to fifteen feet wide, encompassing up to 8.5 acres of the watershed. Bioretention facilities are designed for one-half foot of ponded depth, 36 inches of plant and soil media, and including free-flow underdrains set three feet below the bottom of the basin. The contributing drainage area to bioretention facilities includes up to 17.5 acres of impervious area and 23.1 acres of pervious area.

4.2 Pervious Pavement

Pervious pavements contain small voids that allow stormwater to drain through the surface to an aggregate storage area, then infiltrate into the soil. Site applications include modular paving systems (concrete pavers, grass-pave, gravel-pave) or poured in place solutions (pervious concrete, pervious asphalt). Pervious pavement is an alternative to impervious hardscapes, reducing the effective impervious area. This practice is able to attenuate flow and reduce volume. The pavement layer and aggregate subbase provide rapid infiltration. Total volume retention is dependent on properties of native soils. Pervious pavement is generally used to manage rain that falls on the surface, rather than run on from other areas.

Pervious pavement is typically used to replace traditional impervious pavement for most pedestrian and vehicular applications, other than high-volume / high-speed roadways. Example applications include pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways (Figure 4-7). Pervious pavement systems are typically sized for common storm events (e.g., WQv).

Figure 4-7. Chagrin area pervious pavement.

Pervious pavement was assumed to be applicable throughout the watershed. It was assumed that the entire roadway surface area (not including driveways or aprons) could be converted into pervious pavement. The pervious pavement design includes a two foot deep gravel bed with a free-flowing underdrain set 18 inches below the pavement. The contributing drainage area would be equal to the roadway itself, driveways, and contributing roof and urban lawn areas treating a maximum of 39.5 impervious acres and 44.9 pervious acres. Roads are delineated using GIS, and driveway areas are estimated using a representative number of homes in each of the pilot areas.

4.3 Infiltration Trench

An infiltration trench is an excavated trench lined with filter fabric and backfilled with stone to allow stormwater to infiltrate into subsurface soils. Infiltration trenches are well suited for roadway medians and shoulders, particularly where available space is limited. This practice allows the volume of stormwater discharges to be reduced by promoting infiltration and allowing runoff to percolate into native soils through the sides and bottom of the trench.

Infiltration trenches must be used in conjunction with pretreatment BMPs such as filter strips or other sediment capturing devices to prevent sediments from clogging the trench. Infiltration trenches are typically sized for common storm events (e.g., WQv).

4.4 Rain Barrel

Rain barrels capture and store rainwater as a means of reducing stormwater runoff and providing a non-potable water source for irrigation. This practice is very simple and is used primarily on single-family homes. Rain barrels are usually situated at the discharge point of roof down spouts, and are a convenient source of water for gardening. Rain barrels are sold commercially or sometimes available through local municipalities. Due to their small size, rain barrels usually do not have a measurable effect on reducing runoff volumes.

Rain barrels are typically applied in residential areas. It was assumed that up to half of the homes in the residential area could be retrofitted with up to two rain barrels. Half of the homes with rain barrels are assumed in sequence with bioretention. . The sequence assumes that the entire rain barrel volume is released by opening a bottom orifice two days after the end of a storm. The stored water is used to irrigate bioretention vegetation. The rain barrel capacity at any point during the simulation is a function of the amount of water released after a previous event. Back-to-back events can show bypass, with no rain barrel benefit, if filled to capacity. During cold-weather conditions, the rain barrels are assumed to be disconnected from rooftop downspouts.

The standard size of rain barrels in this application was 55 gallons, with a maximum of two units per home. The drainage area to each rain barrel is assumed to be equal to one-quarter of the roof area, on average 493 square feet based on review of aerial photography.

4.5 Detention Pond

A dry detention pond was modeled in *SUSTAIN* to treat the full drainage area of the watershed. While there is not existing land area in the Mentor Estates test area, the applicability of this BMP to other areas in the Chagrin watershed warranted its inclusion. The pond was assumed to be five feet in depth with a two-stage outlet to provide rate control and draw the pond down over time. The surface area of the pond was considered as a decision variable to a maximum of six acres (roughly eight times the contributing impervious drainage area).

5. Opportunities and Constraints

BMPs are simulated within *SUSTAIN* according to specific design specifications, with the performance modeled using a unit-process parameter-based approach. This contrasts with and has many advantages over most other techniques that simply assign a single percent effectiveness value to each type of practice. *SUSTAIN* predicts BMP performance as a function of its physical configuration, storm size and associated runoff intensity and volume, and moisture conditions within the BMP.

Many of the distributed practices were simulated in aggregate, recognizing the scale and model resolution of the LSPC watershed model. The aggregate approach is a computationally efficient and analytically robust approach that *SUSTAIN* provides for evaluating relative management practice selection and performance at a small subwatershed scale.

An aggregate BMP consists of a series of process-based optional components, including on-site interception, on-site treatment, routing attenuation, and regional storage/treatment. Each aggregate BMP component evaluates storage and infiltration characteristics from multiple practices simultaneously without explicit recognition of their spatial distribution and routing characteristics within the selected watershed. For example, rain barrels within the aggregate BMP network are modeled in series with rain gardens, and service residential rooftop runoff area. Figure 5-1 is a schematic diagram of aggregate components, drainage areas, and practice-to-practice routing networks.

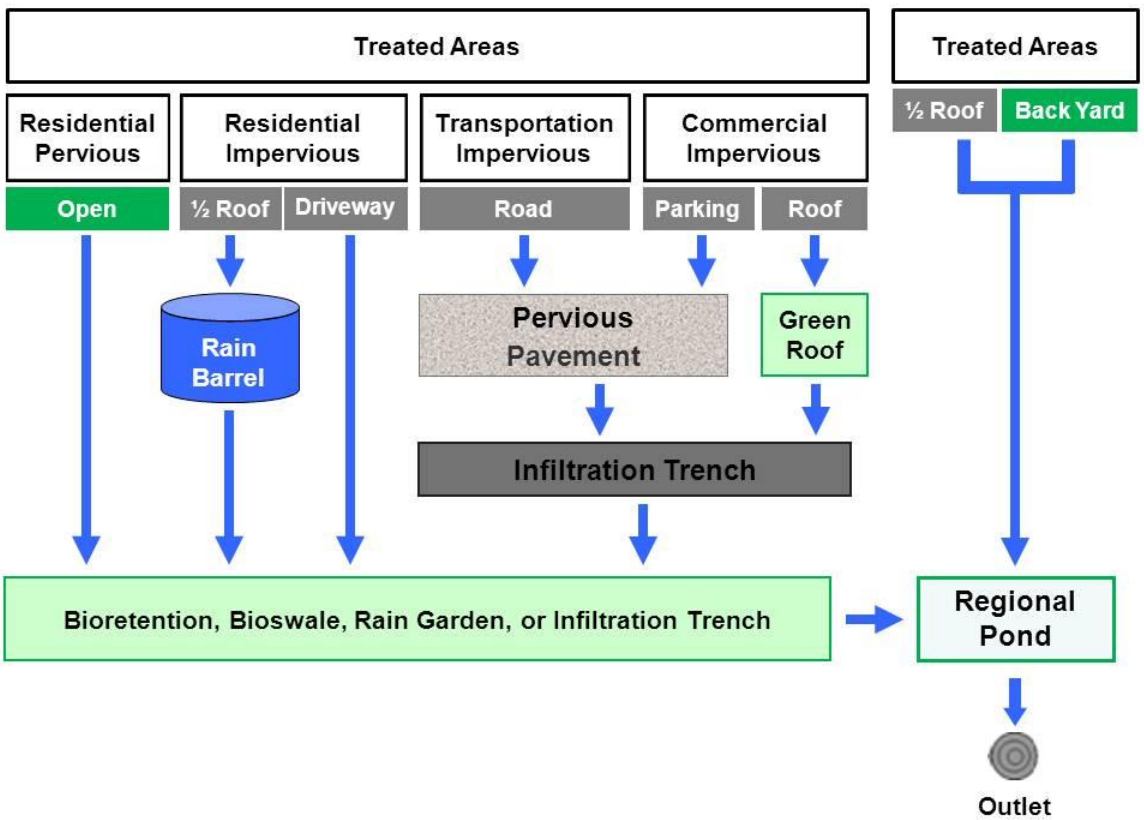


Figure 5-1. Aggregate BMP schematic identifying treatment train options.

5.1 Mentor Estates

The Mentor Estates test area contains soils with relatively low permeability and is susceptible to a high water table. Infiltration basins and trenches were not considered among the suite of applicable practices for this test area. There is also very limited potential use of green roofs and cisterns in this area due to the type of land use and buildings within the subdivision. These practices were also not considered in the analysis. BMPs that were evaluated for application within the Mentor Estates test area include:

- Bioretention (rain garden, bioswale, and bioretention)
- Pervious pavement
- Rain barrels in series with rain gardens
- Detention pond

Three types of bioretention practices were examined in the Mentor Estates test area: (1) rain gardens; (2) bioswales; and 3) bioretention facilities.

For the Mentor Estates test area, the aggregate practice included five component practices—rain barrels, rain gardens, bioswales, bioretention, and pervious pavement. As shown in Figure 5-1, the rain barrel component collects runoff from rooftops (as part of the impervious surfaces) in residential areas. Outflow and bypass from the rain barrel is assumed to flow directly to bioretention, as are front yards and driveways. Other impervious pavement areas can be treated by pervious pavement, and outflow from pervious pavement is routed to certain bioretention practices. Under field conditions, bioretention could then flow back to pervious pavement if downstream areas with surface storage capacity are not being fully used; however, simulation of this backwater condition is a limitation in *SUSTAIN*. Therefore, one directional flow from pervious pavement to bioretention is assumed.

Outflows from pervious pavement, and bioretention, and any other runoff from any type of land use that is not subject to treatment by any aggregate practice components, are routed directly to the outlet. Note that the aggregate BMP setup is a tool to determine which BMP(s) are most efficient at achieving a management objective(s) without representing each individual BMP explicitly (e.g., representing rain barrels for each roof in the study area). The configuration of BMP routing in the aggregate setup are meant to represent a treatment train that makes sense given the BMP design characteristics. Just because a type of BMP is included in the aggregate, it does not mean that it will be used after optimization analysis is performed, as described below.

To run the optimization analysis, a set of decision variables was identified to explore the best possible combinations of the various BMP practices. For this analysis, the decision variables consisted of the following:

- Number of fixed-size rain barrel and rain garden units
- Surface area of bioretention areas, pervious pavement, and detention pond

Because the decision variable values can range anywhere between zero to a maximum number of units or length, it is possible for one component in the treatment train to never be selected if it is not cost-effective toward achieving the objective. For example, even though the aggregate BMP setup includes rain barrels, if rain gardens are found to be a more cost-effective solution under all conditions, all roof runoff will be directly routed to available rain gardens. In other words, the aggregate BMP provides a menu of options that might or might not be selected, depending on cost-effectiveness. During an optimization run, if the size value of zero for a practice is selected, that point will act as a transfer node in the network (i.e., inflow = outflow with no treatment), and the associated cost that is a function of the number of practices or surface area will, in turn, compute to be zero.

Infiltration parameters were determined on the basis of the assumed soil substrate. The background infiltration rate refers to the infiltration rate of the native soils below the engineered media. The vegetative parameter, or the percent vegetative cover, and wilting point values were provided by Tetra Tech, Inc. (2001). Wilting point is defined as the minimum soil moisture required to prevent vegetation from wilting.

Table 5-1. BMP configuration parameters.

Parameter	Rain barrel	Rain garden	Bioswale	Bioretention	Pervious pavement	Detention pond
Physical configuration						
Unit size	55 gal	200 ft^2	N/A	N/A	N/A	N/A
Design drainage area (acre)	0.011	0.044 impervious 0.07 pervious	N/A	N/A	N/A	N/A
Substrate depth (ft)	N/A	2	3	3	1.5	0.1
Underdrain depth (ft)	N/A	N/A	1	1	2	N/A
Ponding depth (ft)	N/A	0.5	0.5	0.5	0.1	5
Infiltration						
Substrate layer porosity	N/A	0.4	0.4	0.4	0.45	0.3
Substrate layer field capacity	N/A	0.25	0.25	0.25	0.055	0.25
Substrate layer wilting point	N/A	0.1	0.1	0.1	0.05	0.1
Underdrain gravel porosity	N/A	N/A	0.5	0.5	0.5	N/A
Vegetative parameter, A	N/A	1	1	1	1	1
Background infiltration rate (in/hr)	N/A	0.10	0.10	0.10	0.10	0.05
Media final constant infiltration rate (in/hr)	N/A	0.5	0.5	0.5	1	N/A

5.2 Great Lakes Mall

An important part of BMP targeting and optimization is the ability to examine opportunities and estimate the general performance or effectiveness of practices at the watershed-scale. Many methods exist to quantify volume and pollutant reductions for large-scale centralized BMPs. In contrast, less information is available to conduct similar evaluations for on-site distributed BMPs. A key objective in reviewing potential opportunities is to develop information regarding the level of implementation that may be needed to achieve management objectives.

At the watershed-scale, it is seldom practical (or even necessary) to attempt to build a model that includes all individual BMPs in each subwatershed (distributed and centralized). Data and / or resource constraints often outweigh the benefit of incorporating details for every site into the overall assessment. However, there are methods to represent a consolidated BMP response within specific management categories or subwatersheds. This can greatly reduce the computational effort, yet still provide a powerful tool for BMP loading analyses, optimization, and selection. An objective of the Chagrin pilot effort is to explore these options.

A goal of the Ward / Newell targeting and optimization pilot effort is to provide tools that are functional and can be used by staff involved with design and placement of stormwater BMPs. Another aspect of BMP targeting and optimization is identification of management opportunities consistent with site suitability considerations. As discussed earlier, differences in soil types between the test areas is a key factor that determines performance of structural BMPs.

A screening level analysis provides a starting point to evaluate the benefits of GI and LID. No quantitative measures have been developed to address excess stormwater runoff in the Chagrin River watershed. However, peak flow rates and total runoff volume are major concerns that contribute to the impairment of aquatic life uses. Consequently, management objectives for this project center on Ohio's water quality volume (WQv) treatment requirement. In Ohio, the WQv treatment requirement is used to guide BMP sizing for practices such as detention ponds. A screening level analysis developed using WQv enables an initial examination of runoff volume; in this case, the amount that results from a 0.75 inch event over a 24-hour period.

In short, the screening analysis provides a platform that supports an examination of various alternatives while accounting for site-specific differences. The primary focus of the screening analysis is to examine the level of treatment that could be applied (e.g., BMP treatment capacity and percent area treated). This is typically developed on a catchment or sub-catchment basis. Treatment capacity is quantified as consolidated storage (e.g., BMP surface area, ponding volume, etc.).

At a small scale (site or local), the BMP representation framework can be applied using models to explicitly simulate the benefits of individual practices. However, at the watershed-scale, there are many more BMP units scattered across the landscape. This poses a challenge in terms of evaluating the collective benefits of distributed BMPs. The required simulations and cost comparisons for the range of distributed BMP opportunities place a significant burden on the computational accuracy and simulation time for system modeling.

One approach to address this challenge is to conduct the screening analysis using a *consolidated network* of BMPs. A *consolidated network* examines various options using different practices and configurations for land categories of interest. Specifically, runoff estimates of the different surfaces, both pervious and impervious, for each land use class provide a starting point. Impervious surface types include roof, road, walking surface, and driving surface other than road (e.g., driveways, parking lots). These surface types can then be used to identify consolidated BMP opportunities and estimate performance.

The screening analysis is structured to evaluate the relative effect of different BMP configurations that focus on treating runoff from specific impervious surface types. An important aspect is to look at the sensitivity of key variables of interest. For example, one potential BMP configuration is the use of pervious pavement in commercial parking areas. Key design variables include the fraction of parking area converted to pervious pavement, characteristics of the subbase (e.g., depth, porosity, etc.), and the native soil infiltration rate.

Figure 5-2 presents the results of a screening analysis for pervious pavement in parking areas. This particular graph depicts volume reduction as a function of the percentage of parking area converted to pervious pavement (addressing a key question related *level of implementation*). The screening analysis is constructed in a way that shows the sensitivity major design variables (e.g., subbase depth or native soil infiltration rate).

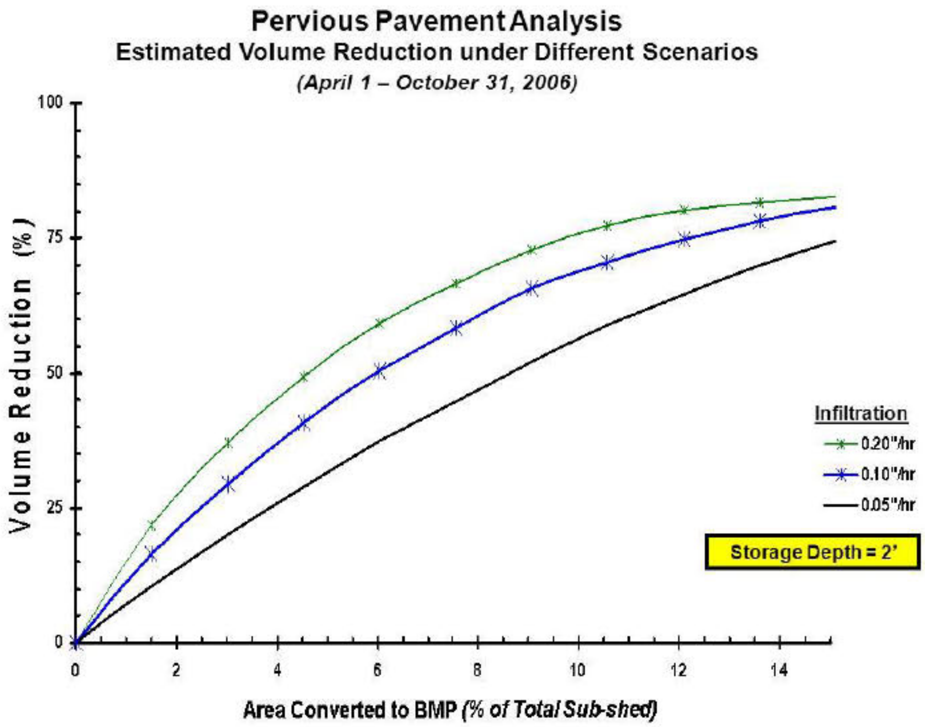


Figure 5-2. Pervious pavement volume reduction estimates at different treatment levels.

In the Figure 5-2 example, a *consolidated network* was employed (in practice, however, pervious pavement would likely be implemented at a variety of points throughout the parking lot). Hourly output from the watershed model was used to generate stormwater volumes. Under a *consolidated network*, the entire parking lot runoff was then routed to one treatment area. The BMP model estimated the amount of water leaving the treated area (either through infiltration or runoff) to determine volume reduction based on user-defined design parameters.

The curves generated in the screening analysis provide a tool that can be used to support advance planning efforts. The curves define a relative range of volume (or pollutant) reductions that might be expected using BMP configurations of interest. However, ultimate BMP performance is driven by design specifications determined through actual field measurements.

The CRWP and the City of Mentor identified four GI practices for potential use in the GLM pilot area (Table 5-2).

Table 5-2. GI practices considered.

GI Practice	Model Representation
Bioretention	Bioretention
Infiltration	Infiltration trench
Underground detention with infiltration	Dry pond
Pervious pavement	Pervious pavement

Each of these practices was evaluated for applicability within the five mall area sub-sheds based on a review of aerial imagery. Applicability was based on available land area and proximity to sources of runoff and pollutants. Applicability of GI practice specifications in the model assumes a mix of fill and native sandy soils. It should be noted that actual implementation of these practices will also have to consider infiltration rules found in the Ohio Rainwater and Land Development manual (Ohio DNR 2006).

Figure 5-3 and Figure 5-4 present the results of a screening analysis for the potential use of bioretention in the GLM parking area. As discussed earlier, these graphs depict volume reduction as a function of the percentage of parking area converted to bioretention.

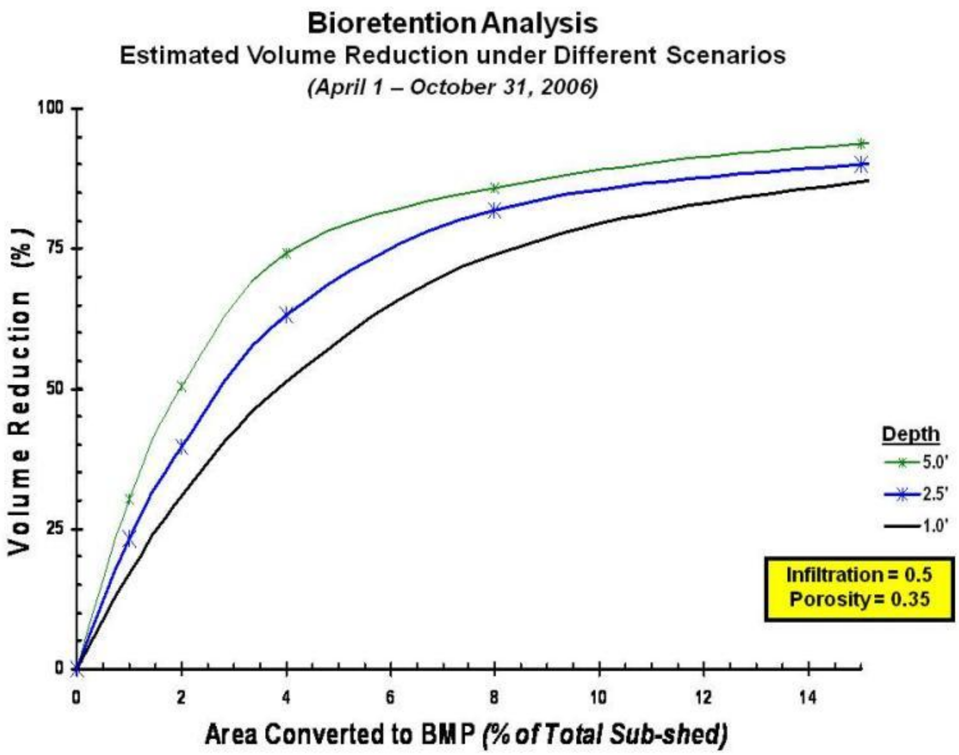


Figure 5-3. Bioretention volume reduction estimates at different storage depths.

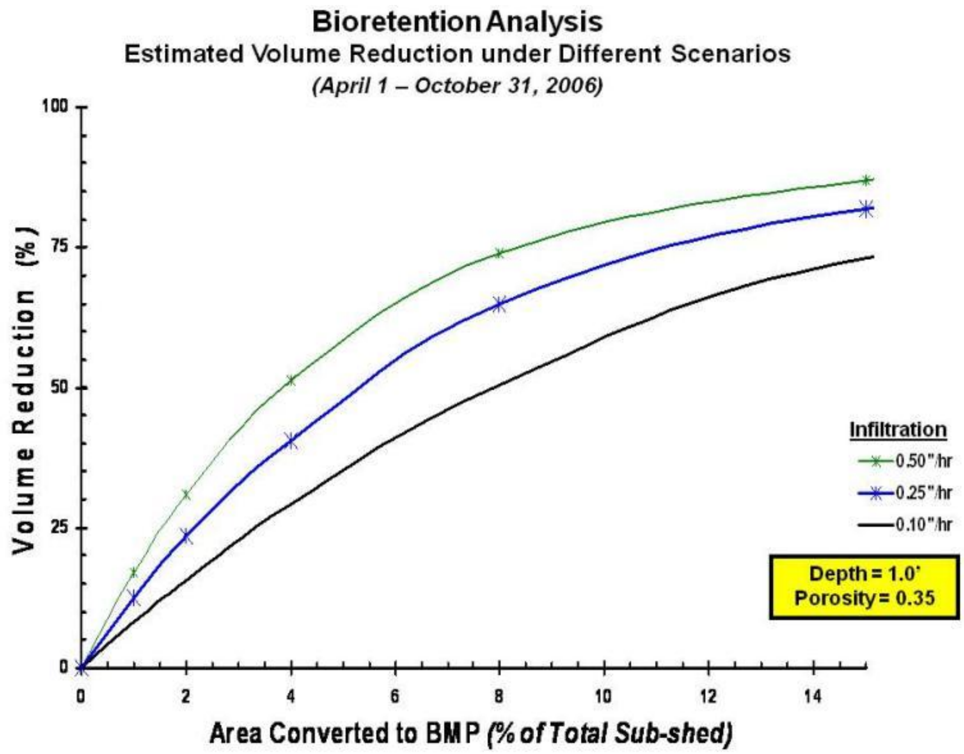


Figure 5-4. Bioretention volume reduction estimates at different infiltration rates.

6. Costs

Cost functions are mathematical formulations used to estimate financial expenditures associated with BMP implementation. These represent the combined costs of specific BMP designs, materials, land / space requirements, and operation / maintenance. Cost estimates are essential for the optimization phase of the project.

The purpose of this activity is to ensure that occurs to develop appropriate cost functions. Comprehensive work on stormwater BMP costs was conducted as part of the Rouge River National Wet Weather Demonstration Project in Michigan (*Cost Estimating Guidelines: Best Management Practices and Engineering Controls*, 1997 and 2001 update). Some cost estimates for stormwater BMPs are available as part of local watershed plans, such as the *St. Joseph River Watershed Management Plan* (Indiana / Michigan).

Other work conducted in the Great Lakes Region includes a University of Minnesota (UMN) report *The Cost and Effectiveness of Stormwater Management Practices*. UMN staff collected and analyzed construction, operation, and maintenance cost data for a range of stormwater management practices. These included dry detention basins, wet basins, sand filters, constructed wetlands, bioretention filters, infiltration trenches, and swales using literature reported on existing sites across the United States.

Cost information has also been compiled in other parts of the country to support BMP targeting and optimization efforts. Examples include work in the Charles River, Massachusetts, Vermont, and Southern California.

Cost data represents life cycle costs by considering three categories of BMP costs:

- Probable Construction Costs – The initial cost to construct the BMP
- Annual Operation and Maintenance – The annual costs to maintain the BMP
- Repair and Replacement Costs – The additional costs to repair or replace the BMP

A standard unit cost was defined for each BMP category, since the range of BMPs was unknown and expected to vary significantly (Table 6-1). Each unit cost was converted to 2012 dollars by applying a three percent inflation rate from the published year of the cost data to 2012. A discount rate of three percent was used for converting annual operation and maintenance and repair and renewal costs to present value.

The lifecycle period was defined as 20-years to take into account costs for replacing some BMPs. Several of the sources used to derive costs data defined engineering and design and/or contingency factors based upon a percent of the base construction cost, while other sources intentionally omitted them. A default 15 percent engineering and design cost factor and 25 percent contingency cost factor were assigned to probable construction costs when no values were provided. No land, administration, demolition, or legal cost factors were defined for any of the probable construction costs.

Table 6-1. BMP costs.

Parameter	Rain barrel	Rain garden	Bioswale	Bioretention	Pervious pavement	Detention pond
Life Cycle Cost Data						
Lifecycle Unit Cost [A+B+C] (NPV)	$165.69 ea	$13.6/ft^2	$36.80/ft^2	$38.73/ft^2	$16.58/ft^2	$18.95/ft^2
A) Probable Unit Cost	$95.00 ea.	$7.80/ft^2	$26.07/ft^2	$28.00/ft^2	$12.38/ft^2	$11.53/ft^2
Annual O&M	$0	$0	$0.72/ft^2	$0.72/ft^2	$0.28/ft^2	$0.15/ft^2
B) Annual O&M (NPV)	$0	$0	$10.73/ft^2	$10.73/ft^2	$4.20	$2.17/ft^2
C) Repair & Replacement (NPV)	$70.69 ea.	$5.8/ft^2	0	0	0	$5.25/ft^2
BMP Lifecycle Period	10-yrs	10-yrs	20-yrs	20-yrs	20-yrs	10-yrs (Repair & sediment removal)

NPV – Net Present Value

The following sources were reviewed when defining the lifecycle costs:

- WERF. 2009. BMP and Low Impact Development Whole Life Cost Models version 2.0. Water Environment Research Foundation.
- Center for Neighborhood Technology. June 30, 2009. National Green Values Calculator.
- University of Minnesota. Peter T. Weiss, John S. Gulliver, Andrew J. Erickson. June 2005. The Cost and Effectiveness of Stormwater Management Practices. Prepared for Minnesota Department of Transportation.
- Low Impact Development Center, Inc. November, 2005. Low Impact Development for Big Box Retailers". Prepared for U.S. Environmental Protection Agency. Prepared by the Low Impact Development Center, Inc.

The City of Toledo, Ohio and Burnsville, Minnesota provided cost data for design and construction of bioswales and bioretention, respectively, and Chagrin River Watershed Partners provided review and input on cost data based on watershed experience. Additional Tetra Tech projects and best professional judgment were also considered when defining the range of lifecycle unit costs.

7. Targeting and Optimization

The objective of the Mentor Estates optimization was to evaluate reduction in annual flow volume using the previously described suite of practices in three subwatersheds all upstream of a potential detention pond. The analysis assumed background infiltration rates consistent with HSG C; however, since there is typically a great deal of spatial heterogeneity with soils, assigning a single soil group greatly simplifies the true complexity of site conditions. In assessing the study objective and quantifying the uncertainty associated with soil assumptions, this analysis will:

- Develop a cost-effectiveness curve for annual volume reduction
- Identify solutions of interest at various points along the curve from which to evaluate specific BMP selections by practice and subwatershed
- Test the sensitivity of the soil parameter assumptions by running alternative model scenarios for each selected solution with assumptions consistent with HSG-D

Runoff time series were generated using a calibrated LSPC watershed model from the neighboring Grand River Watershed located approximately five miles east of the Mentor Estates study area. The Grand River watershed model was calibrated using the Painesville NCDC station (336389); however, observed precipitation data from the Painesville NCDC station (336389) was substituted as input to the watershed model to generate runoff time series for use in the *SUSTAIN* Mentor Estates model. Precipitation patterns at the Painesville NCDC station are more representative of the conditions expected around Mentor Estates.

Rather than just running a single model simulation, *SUSTAIN* uses information from a series of model runs to arrive at a near optimal set of solutions. For the sake of efficiency, it is often prudent to limit the modeling scope to a period of time representative of a critical condition (ie. low flow, high flow, average precipitation). Figure 7-1 presents an annual summary of precipitation at the Painesville NCDC station. For this study, a simulation period of January 1, 2003 through December 31, 2003 was selected to represent a near-average precipitation year.

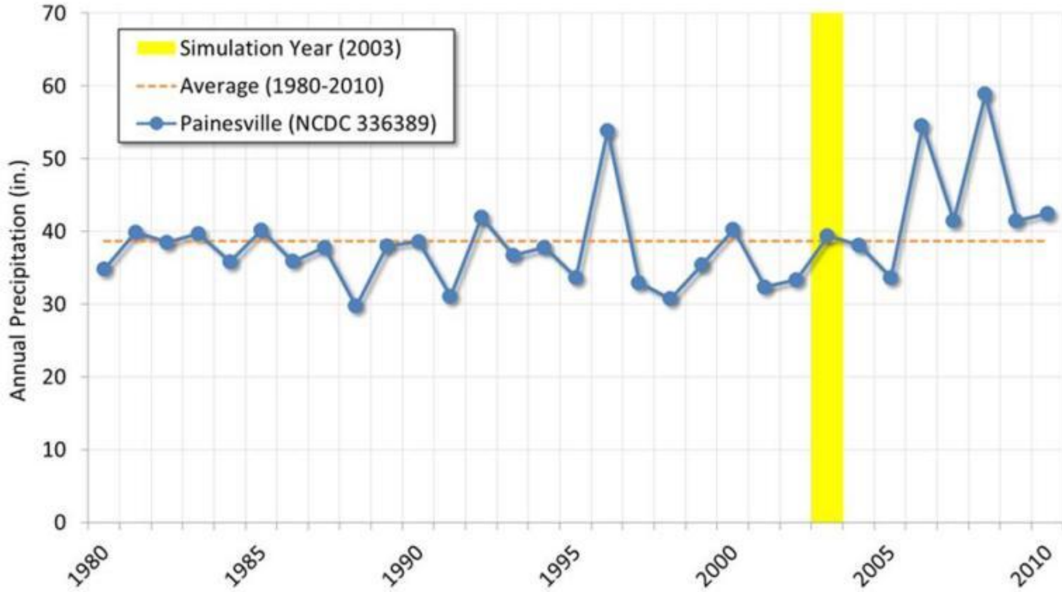


Figure 7-1. Annual precipitation for the Painesville (336389) NCDC station.

Figure 7-2 shows a map of the Mentor Estates *SUSTAIN* model setup in ArcGIS. The model is organized into three subwatersheds as previously outline in Figure 2-24. Each subwatershed has been configured with one aggregate BMP consisting of (1) rain barrels (2) pervious pavement, and (3) bioretention, bioswale, or rain gardens. Each of the three aggregate BMPs flows to a single detention pond just upstream of the network outlet.

As noted, this detention pond is hypothetical for the purposes of this study as no specific location has been identified; however, there is likely opportunity in neighboring areas for this type of practice. Aggregate BMP components were defined consistent with the representation outlined in Table 5-1. The maximum extent of decision variables for each BMP was configured as discussed in Table 2-2. All decision variables were allowed to vary at 10 percent increments of their maximum value. The optimization model was set to simulate 20,000 model runs which took just under two hours to complete.

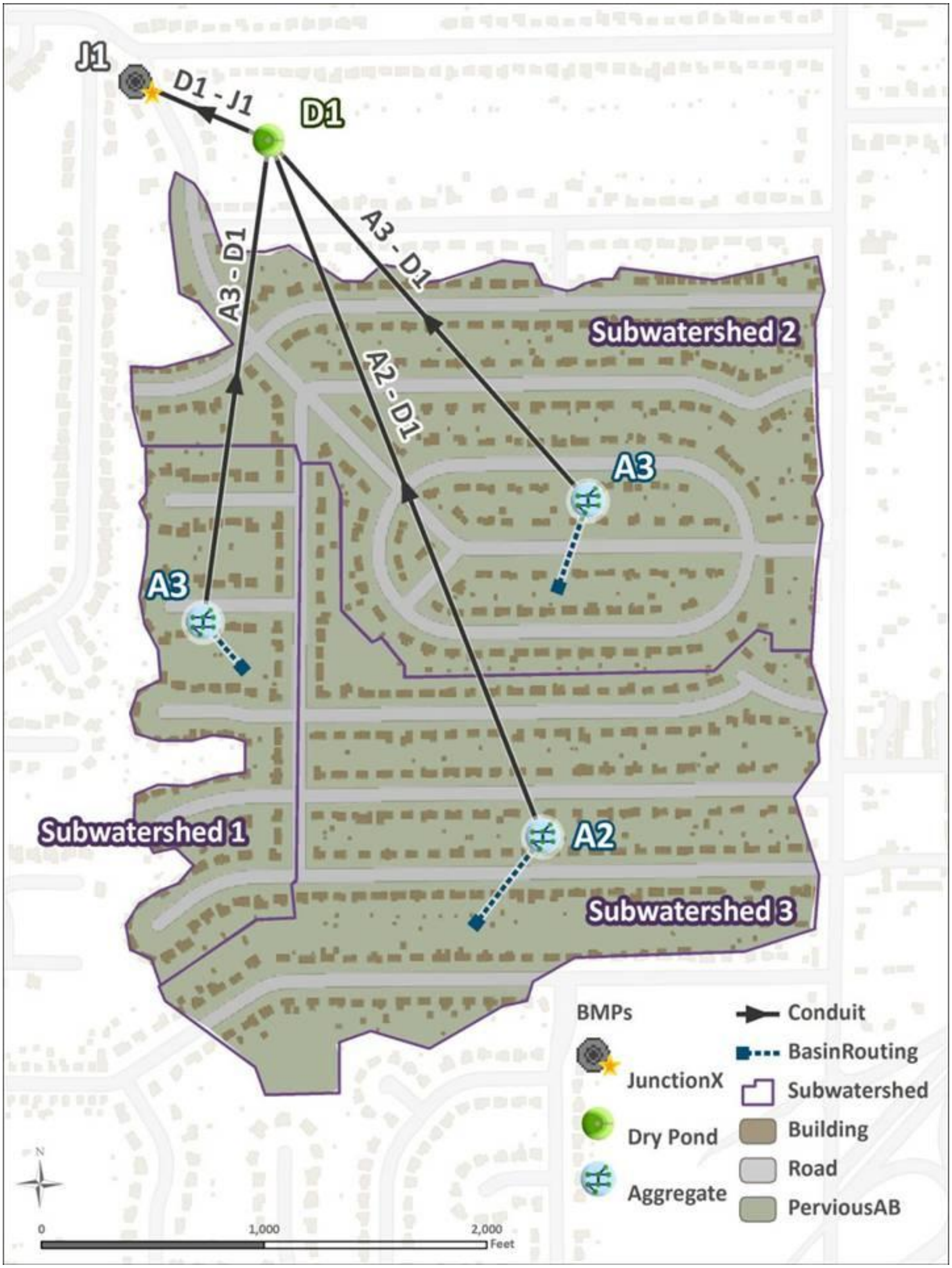


Figure 7-2. Map of the Mentor Estates *SUSTAIN* model configuration.

Figure 7-3 shows the average annual stormwater runoff volume reduction cost-effectiveness curve for the study area as a result of running the *SUSTAIN* model for a representative one year period. In this figure, the small points represent all solutions that were evaluated during optimization, while the larger points along the left-and-upper-most perimeter represent the least cost options at each volume reduction interval. The maximum achievable volume control through the use of all potential GI practices within the study area is just over 80 percent; however, there is clearly a point(s) above which the marginal costs of additional controls increases dramatically. Six solutions were selected for detailed performance evaluation at different intervals along the curve (the larger, circles points on the curve). These solutions were selected to demonstrate management options at increasing levels of annual flow volume control.

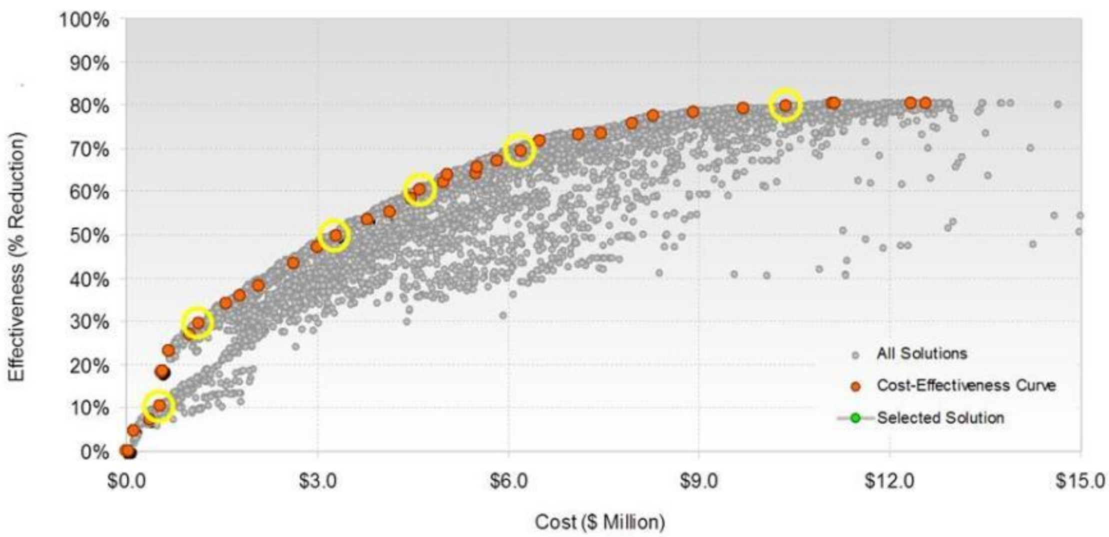


Figure 7-3. Cost-effectiveness curve for annual flow volume reduction in Mentor Estates test area.

To investigate the efficiency of treatment in each pilot area subwatershed the treatment depth of each was assessed for all solutions. Treatment depth was calculated as the treated volume divided by the contributing impervious drainage area (51.6 acres). If the BMPs in a subwatershed were 100 percent efficient the BMP network would, in effect, treat all rainfall that was captured by the contributing drainage area. The average annual rainfall for the modeled time period (January 1, 2003 through December 31, 2003) is 38.4 inches while the annual runoff in the *SUSTAIN* baseline is 34.6 inches. The closer the treatment depth to this annual runoff value (34.6 inches), the more efficient the BMP network within a subwatershed was at treating storm flows.

Table 7-1. Selected near-optimal solutions for evaluating BMP utilization by subwatershed

Solution number	BMP cost (million $)	Annual flow volume reduction (%)	Annual runoff depth treated (inch)
1	0.53	10.5	3.6
2	1.15	29.5	10.2
3	3.30	52.0	18.0
4	4.61	60.5	21.0
5	6.21	69.2	24.0
6	11.13	80.3	27.8

Considering the relatively low infiltration capacity of native soils at Mentor Estates, a maximum annual average flow reduction of over 80 percent appears high; however, the modeled extent of pervious pavement is the key to understanding the trajectory of this cost-effectiveness curve. Recalling the screening analysis for pervious pavement presented in Figure 5-2, for a fixed drainage area the maximum achievable flow reduction is a function of the BMP size. While the background infiltration rates limit the slope of the BMP curve, the size of the BMP also has great influence on the achievable flow reduction. In Figure 5-2, pervious pavement was shown to achieve annual average flow reductions near 75 percent even with a background infiltration rate of 0.1 inch per hour when the BMP was sized to approximately 15 percent of the contributing impervious drainage area. In this pilot study application, 100 percent of the imperious road was considered for conversion. While in reality the feasibility of this is dependent on a number of factors not considered by this study, it does offer some explanation into the cost-effectiveness curve.

The Mentor Estates optimization was configured to assess the annual reduction in flow volume through the use of distributed, neighborhood scale LID practices in three subwatersheds. Figure 7-4 illustrates how utilization changes for each BMP by subwatershed for the selected solutions as both cost and percent volume control increase.

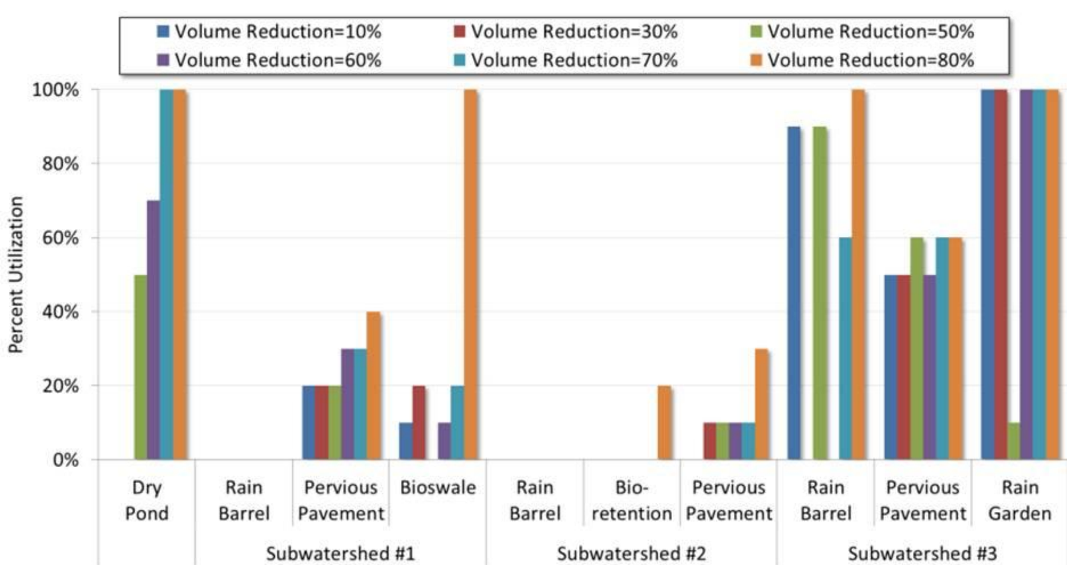


Figure 7-4. Percent utilization of BMPs by subwatershed.

Figure 7-4 illustrates the during the optimization process, some BMPs were highly favored and almost always utilized, others were relied upon more heavily for increasing levels of management, and still others were never considered to be cost-effective treatment options. The following conclusions can be drawn by examining Figure 7-4:

- Pervious pavement was consistently used in all three subwatersheds for almost all solutions at implementation levels of 10-60 percent. This practice was likely selected not only based on cost, but also due to the large area of opportunity. In this analysis, all streets were considered available for pervious pavement; however, the feasibility of implementation at this level requires field assessment beyond the scope of this analysis.
- Rain Gardens (Subwatershed 3) were completely utilized for almost all selected solutions suggesting that these practices are heavily favored, primarily since the unit cost used in the model reflects lower-cost installation by homeowners. The drop in rain garden utilization for Solution 3 appears to have been compensated for with pervious pavement. It is also coincident with the introduction of the regional detention pond facility.
- Rain barrels were generally unfavorable in this analysis with the exception of Subwatershed 3. The erratic selection between solutions again suggests that rain barrels are generally unfavorable and can be easily compensated for with other practices.
- Detention Ponds, even though primarily used to hold stormwater for a controlled release, provided some volume reduction during the simulation through background infiltration and evaporation; however, this practice was only selected for flow reduction targets somewhere between 30-50 percent.
- Bioretention (Subwatershed 2) was only utilized for achieving the highest flow reduction (80 percent). This BMP was parameterized with the highest unit cost, although unit cost for the *SUSTAIN* model were based on BMP footprint and not storage volume.

Sensitivity analysis has shown that the background infiltration rate is one of the most sensitive BMP parameters in *SUSTAIN* (Shoemaker et al. 2012). The cost-effectiveness curve presented in Figure 7-3 is based on assumptions of pervious runoff time series and BMP infiltration rates consistent with HSG-C soils. A reduction in infiltration rates from HSG-C to HSG-D can dramatically impact the results of the optimization model. To test the sensitivity of the soil group assumption, two parallel optimization models were developed using runoff boundary conditions and BMP parameters consistent with both HSG-C and HSG-D site conditions. Background infiltration rates for HSG-D were set at 0.08 inch per hour consistent with parameterization of soil conditions in the lower Grand River Watershed TMDL model (Tetra Tech 2011).

The two models each generate unique cost-effectiveness -curves which, when super-imposed as a single plot, produce cost-effectiveness bands that capture the uncertainty inherent in the model assumptions and bracket the expected runoff response to LID practices. Five unique solutions (points on the cost-effectiveness curve) were selected for comparison. The results of this sensitivity analysis comparing HSG-C and HSG-D assumptions are presented in Figure 7-5 and Table 7-2.

Table 7-2. Flow reduction change for selected solutions under different soil group boundary conditions.

Solution number	Solution cost (million $)	HSG-C annual flow reduction (%)	HSG-D annual flow reduction (%)
1	0.53	10.5	9.4
2	1.15	29.5	25.7
3	3.30	52.0	48.1
4	4.61	60.5	56.5
5	6.21	69.2	65.1
6	11.13	80.3	76.6

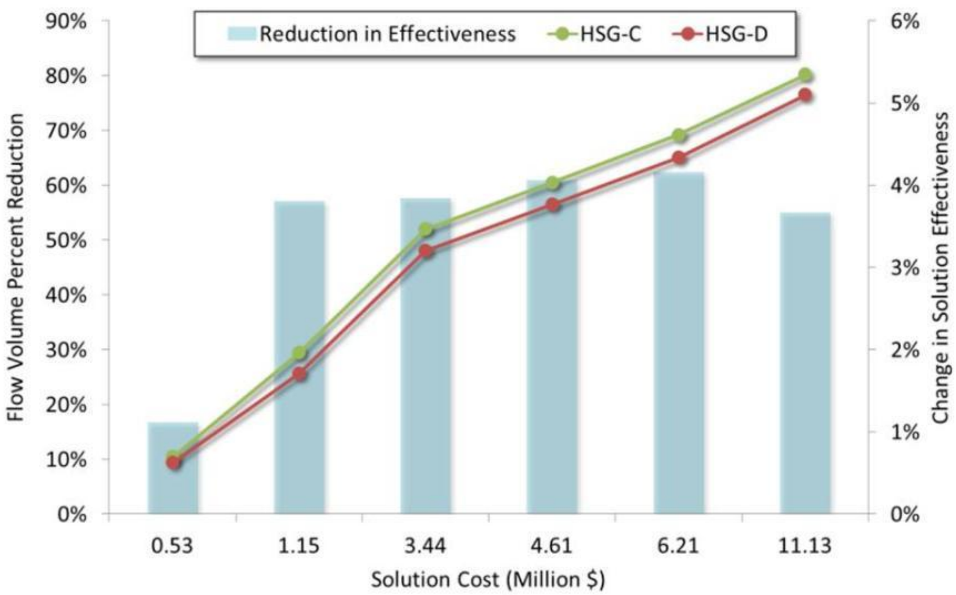


Figure 7-5. Selected solution comparison under different soil group boundary conditions.

As expected, the sensitivity analysis presented in Figure 7-5 shows that assumptions regarding soil properties can produce noticeable differences in BMP performance even when comparing HSG-C and D. In this case the pervious runoff time series and BMP infiltration rates were changed from representing HSG-C at 0.1 inch per hour to representing HSG-D at 0.08 inch per hour. A 0.02 inch per hour decrease in background infiltration rates produced a 1.1 percent to 4.2 percent decrease in BMP performance with regard to annual average flow volume reduction. The impact of these types of assumptions are important to recognize and consider when performing any type of modeling; however, the impacts become even more important to consider during optimization when trade-off in performance versus cost are being evaluated for possible capital implementation.

8. References

American Society of Civil Engineers / Water Environment Federation (ASCE / WEF). 1998. *Urban Runoff Quality Management*. WEF Manual of Practices No. 23, ASCE Manual and Report on Engineering Practice No. 87. Alexandria and Reston, VA.

Chagrin River Watershed Partners (CRWP). December 2009. *Chagrin River Watershed Action Plan*. Willoughby, OH.

Colwell, S. R., et al. 2000. *Characterization of Performance Predictors and Evaluation of Mowing Practices in Biofiltration Swales*. Center for Urban Water Resources Management. Seattle, WA.

Dorsey, J, R. Webb, J. Witter, D. Mecklenburg, and A. Brennan. September 2009. *Modeling the Effectiveness of Traditional and Innovative Stormwater Management Strategies in the Chagrin River Watershed: Part 1 – Development Site Scale*. Chagrin River Watershed Partners. Willoughby, OH.

National Research Council. 2008. *Urban Stormwater Management in the United States*. National Academies Press. Washington, DC.

National Weather Service. 2004. *NOAA Atlas 14: Precipitation-Frequency Atlas of the United States*. Data accessed through: http://hdsc.nws.noaa.gov/hdsc/pfds/. U.S. Department of Commerce. National Oceanic and Atmospheric Administration. Silver Spring, MD.

Ohio Department of Natural Resources. 2006. *Rainwater and Land Development: Ohio's Standards for Stormwater Management, Land Development and Urban Stream Protection*. Third Edition. Division and Soil and Water Conservation. Columbus, OH.

Reese, A. September 2009. *Volume-Based Hydrology: Examining the Shift in Focus from Peak Flows and Pollution Treatment to Mimicking Predevelopment Volumes*. Article in Stormwater.

Rossman, L.A. 2005. Stormwater Management Model User's Manual, Version 5.0 EPA/600/R-05/040. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH.

Shoemaker, L., J. Riverson, K. Alvi, J. X. Zhen, and R. Murphy. 2012. *Report on Enhanced Framework (SUSTAIN) and Field Applications to Placement of BMPs in Urban Watersheds*. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-11/144.

Southeast Michigan Council of Governments. 2008. *Low Impact Development Manual for Michigan: A Design Guide for Implementors and Reviewers*. SEMCOG Information Center. Detroit, MI.

Tetra Tech. 2001. *Low-Impact Development Management Practices Evaluation Computer Module, User's Guide*. Prepared for Prince George's County, Maryland. Fairfax , VA.

Tetra Tech. 2003. *Validating the Low–Impact Development Management Practices Evaluation Computer Module*. Prepared for Prince George's County, Maryland, Department of Environmental Resources. Fairfax, VA.

Tetra Tech. 2011. *Total Maximum Daily Loads for the Grand River (lower) Watershed*. Prepared for Ohio Environmental Protection Agency. Fairfax, VA.

U.S. Environmental Protection Agency. August 2007. *An Approach for Using Load Duration Curves in the Development of TMDLs*. Office of Water. EPA-841-B-07-006. Washington, D.C.

U.S. Environmental Protection Agency. September 2009. *SUSTAIN – A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality*. EPA/600/R-09/095. U.S. Environmental Protection Agency. Office of Research and Development. Washington, DC.

U.S. Environmental Protection Agency. December 2009. *Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act*. Office of Water. EPA-841-B-09-001. Washington, D.C.